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Adaptive Water Management: Alternatives to Close the Supply-Demand Gap in the Northern Colorado Water Conservancy District

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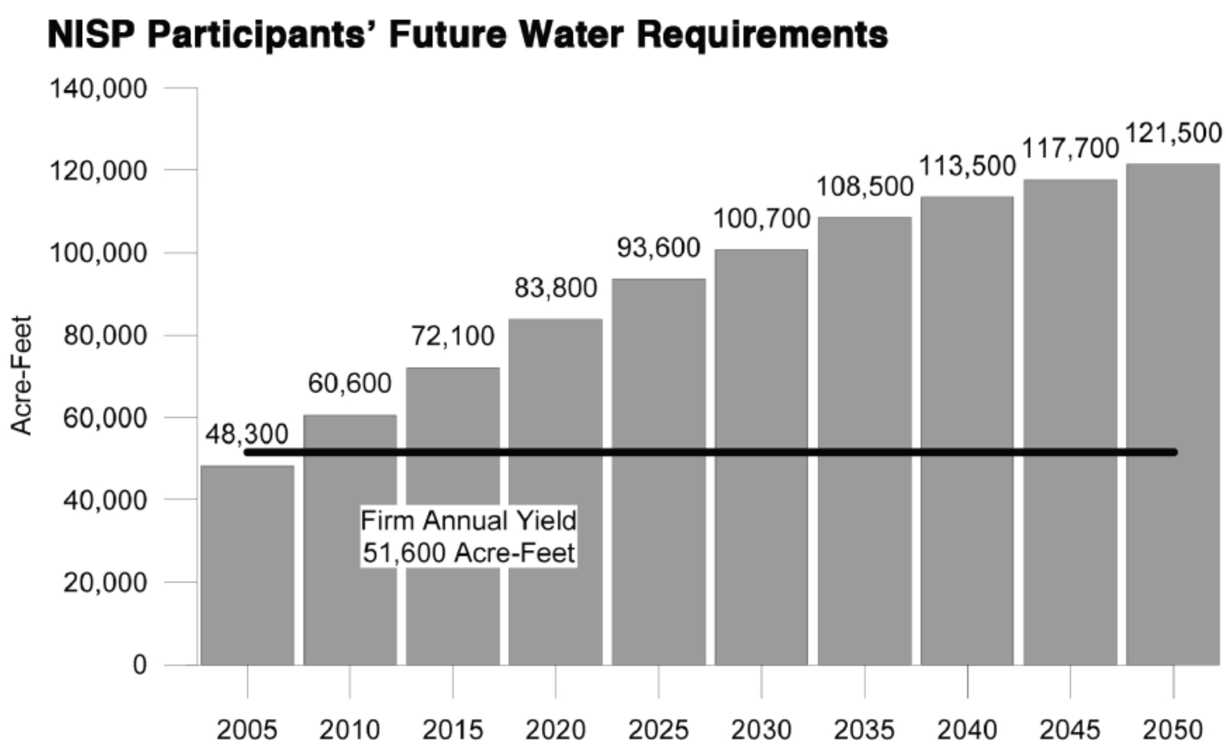
Introduction

The 2014 World Water Development Report and the findings of the Intergovernmental Panel on Climate Change reflect a growing global concern about the integrity of the planet's natural resources. The reports anticipate a future characterized by environmental degradation, conflict, and disasters in the form of intense drought, famine, freshwater shortages, natural disasters, disease, poverty, and resource conflicts (WWDR, 2014) (IPCC, 2014). These projected environmental consequences are widespread and severe; they have demonstrated that humankind is no longer exempt from the constraints of nature; rather, the fate of humankind is intrinsically bound the fate the natural system and its resources (Dunlap, 2001) (Folke et al., 2002). Nowhere are the impacts of resource challenges felt more critically than in the context of water.

Water is a limiting factor of all human life and development. While water is a renewable resource, global freshwater resources are limited and unequally distributed across the globe, posing mitigation challenges for those with too much, and management challenges for those with too little. These challenges are only amplified by population growth, which strains limited resources with ever-increasing demand. In addition to population, climate change threatens to make management of natural resources more difficult, as projections introduce large degrees of uncertainty in distribution, timing, and total precipitation (Nichols, Murphy, & Kenney, 2001) (Fahlund, Choy, Szeptycki, 2014).

The threats presented by population growth and climate change prompt the question of how water providers adapt their management practices to address widely projected supply-demand gaps while maintaining the quality, reliability, and affordability of their water resources. Ideally, this study would gather and analyze information regarding many water management entities, but time and research constraints have limited the scope to one particular case study in the Northern Colorado Front Range Region, and more specifically, the second-largest water provider in the State of Colorado: The Northern Colorado Water Conservancy District (Northern Water). Principally, Northern Water has been selected because it is emblematic of large water providers in water-scarce environments facing water resource challenges related to population growth and climate change. Northern Water will need to surmount a 110,000 acre-feet supply-demand gap projected for 2050 while balancing needs between growing population centers and agricultural production (NCWCD, 2012). In addition, Northern Water is an organization with the infrastructure, financial, and technological resources necessary to explore a number of water supply alternatives, currently undertaking several new projects in order to address projected water shortages within its jurisdiction.



Projected supply-demand gap for a portion of municipalities in the Northern Colorado Water Conservancy District http://www.northernwater.org/WaterProjects/NISPParticipants.aspx

This thesis is organized around two research questions:

1. How will population growth and climate change affect water systems in the Northern Colorado Water Conservancy District?
2. What management alternatives should be implemented to close the projected water supply-demand gap while improving the reliability and sustainability of Northern Water system?

In order to address the research questions guiding this thesis, it is first necessary to provide an extensive literature review of the characteristics affecting water management in the region, including historical perceptions of Colorado's water resources, Colorado's natural climatic condition, population trends, and climate change projections. This background information is fundamental in order to build an understanding of how water management has been approached, what limitations exist, and what management approaches have currently been implemented in Colorado and the Northern Colorado Water Conservancy District.

The literature review introduces the concept of adaptation and adaptive management as a guiding framework for the consideration of management alternatives designed to address the consequences of change and uncertainty in the form of population growth and climate change. The predominant management alternatives are analyzed based on value-based policy analysis method incorporating efficacy, cost-effectiveness, legal feasibility, and equity. Based upon the analysis of the alternatives, it is the objective of this thesis to determine qualitatively and quantitatively the strengths and weaknesses of the water supply alternative(s), thus allowing for the recommendation of which alternatives should be pursued as part of an adaptive management approach within Northern Water. The results of the thesis hold value as a framework not only for closing the water supply-demand gap in Northern Water, but also for many potential water providers and natural resource management agencies who will need to address the impact factors of population and climate change in resource management decisions this century.

Problem Background: Population and Climate

Colorado is a land of beauty, a land of destiny, a land of opportunity. Its vast open spaces capture the hearts and imaginations of its inhabitants with the call of opportunity and resources that appear limitless, but which history and science show to be both finite and very fragile.

"A few tufts of Grass"

Early explorers of Colorado's Front Range—the corridor where the Western shortgrass prairie meets the foothills of the Rocky Mountains—thought permanent, substantial settlement of the semi-arid, sagebrush-covered and windswept lands they encountered would be impossible. One of Colorado's first American explorers, Zebulon Pike, described Colorado's Front Range landscape as "incapable of cultivation" because of the lack of trees and streams on his journey across the plains (Limerick, 2012). In 1849, famed author of *The Oregon Trail,* Bostonian Brahmin Francis Parkman, reached the same conclusion as his predecessor. In describing the vegetation during his journey from Fort Laramie to Bent's Fort, he stated, "there are only a few short tufts of grass, dried and shriveled by the heat (Limerick, 2012).

Most notably, explorer John Wesley Powell published an account of his travels in the West and through Colorado in his 1878 *Report on the Arid Region of the United States.* A Civil War veteran famed for his journey down the Colorado River, his publication on western peoples and places described the challenges to building lives in the nation's new territories and prescribed methods of resource management and settlement. Powell believed that while the water-starved West had supported native populations in its natural state, it would not be able to accommodate the increasing needs of settlers without adapting the prevailing methods of land and resource allotment. His report called for a minimum of 2,560-acre homesteads—in contrast to the typical 160-acres awarded under the Homestead Acts of 1862—citing that smaller lands with denser populations “In general…greatly exceed the capacities of the streams” (Colorado College, 2011). Furthermore, Powell devised a classification system for lands into three categories: timber, pasturage, and irrigable lands. Powell argued that a precursor to any substantial settlement would be large-scale water diversion and irrigation projects that could support agricultural production (Colorado College, 2011).

While historical predictions about the potential of Colorado’s Front Range for settlement have largely proven to be false, insights concerning Colorado’s limited natural resources should not be disregarded: The Colorado Front Range remains to this day, a region characterized by its extremely water-limited ecosystem.

Colorado’s Water Resources

Historically, the availability of water resources has been the most decisive factor in human capability for settlement (Fahlund, Choy, Szeptycki, 2014). In the context of the American West, Patty Limerick describes in her book *A Ditch in Time* that “the comparative scarcity of water has been the principal feature of regional distinctiveness.” While Colorado’s mountains host an abundance of water resources (on average, 16 million acre-feet annually) and claim title to the headwaters of four major rivers (The Colorado, Platte, Arkansas, and Rio Grande), the geographic features of the state limit the availability of water on the eastern side of the Continental Divide (Colorado Water Conservation Board, 2011). Fed by melting snowpack from the high peaks, the major Colorado rivers flow abundantly during the spring and summer months. However, abundance is a relative term, as the rivers of the eastern side of the Continental Divide account for only 14-20 percent of the flows leaving the state, while the rivers west of the Divide account for over 80 percent of the flows (Limerick, 2012).

In Colorado, weather systems pass predominantly from west to east across the Rocky Mountains. As parcels of air move up and over the high peaks, the water vapor rises, expands, cools and condenses, reaching saturation vapor pressure and producing precipitation on the windward side of the mountain peaks. On the leeward side of the Rocky Mountains, air parcels descend and warm, thus resulting in a lower relative humidity and limiting likelihood of precipitation (Roe, 2005). Orographic lifting produces dramatic differences in precipitation over a relatively minor horizontal distance. Consequently, in Colorado, the Western Slope can receive four times the average annual precipitation that the Northeastern Colorado plains receive (NCWCD, 2014).

Population

The large disparity in water distribution across the state is complicated by the size and distribution of human population. Since the early 1970s, the entire Western United States has been experiencing a population boom. The 2000 U.S. Census revealed that the population of western states increased by 32 percent in 30 years, compared to a nationwide average of 19 percent (Nichols, Murphy, & Kenney, 2001). Over the span of a single decade, 2000 to 2010, the population of the West grew by an astounding 13.8 percent, or 8.7 million people (Fahlund, Choy, Szeptycki, 2014). Specifically, the states with the highest growth rates have been those of the “Interior West,” including Colorado. In the past decade, Colorado’s population has grown from just over 4 million to nearly 5.5 million residents (Colorado Department of Local Affairs, 2012). By 2050, Colorado’s population is expected to approach eight million, nearly doubling the population in half a century (Colorado Water Conservation Board, 2011) (Colorado Department of Local Affairs, 2012). Under current per-capita rates of consumption, a larger population will necessitate a larger demand for water.

The arrangement of population growth in Colorado poses new challenges given water availability. The trends observed in Colorado are indicative of the trends observed across the West; the most significant population growth is occurring where the natural resources are least equipped to meet the new demands. For example, the communities of the Northern Front Range have highest growth rate in the state, at 1.9 percent annually (Colorado Department of Local Affairs, 2012). Under medium population growth scenarios, the population of the Northern Colorado Front Range will increase by 70% over the next 40 years (Colorado Department of Local Affairs, 2012). Within Northern Water, this could equal an increase in from approximately 860,000 to more than 1.5 million customers (Colorado Department of Local Affairs, 2012) (NCWCD the Colorado Big Thompson Project, 2014). To provide a comparative example of this change, it equates to "to adding five new cities the size of Denver by 2050" (Western Resource Advocates, 2012). At present, eighty percent Coloradans live to the east of the Continental Divide, with only twenty percent of the population occupying the "Western Slope" (Colorado Water Conservation Board, 2011) (Western Resource Advocates, 2012). Given that the vast majority of the projected population growth will occur where only twenty percent of the surface water is available, the natural and human geography of Colorado seemingly pit climate against population and Western Slope against the Front Range.

Early Innovation

In many ways, the story of Colorado water during the last century has been dominated by the vision to overcome the consequential arrangement of water resources. Since John Wesley

Powell’s journey through the West in the 1860’s, settlers in the Rockies have dammed rivers, built reservoirs, and diverted water for a number of uses. The Reclamation Act of 1902 was one of the most significant pieces of legislation for the creation, expansion and sustenance of agricultural production and population growth in Colorado. In the 20th century, the U.S. Reclamation Service (later the U.S. Bureau of Reclamation) sold public lands to finance water diversion, retention and transmission projects in arid states, including Colorado. The resultant engineering feats allowed for growth and prosperity in a landscape that once seemed incapable of supporting human life.

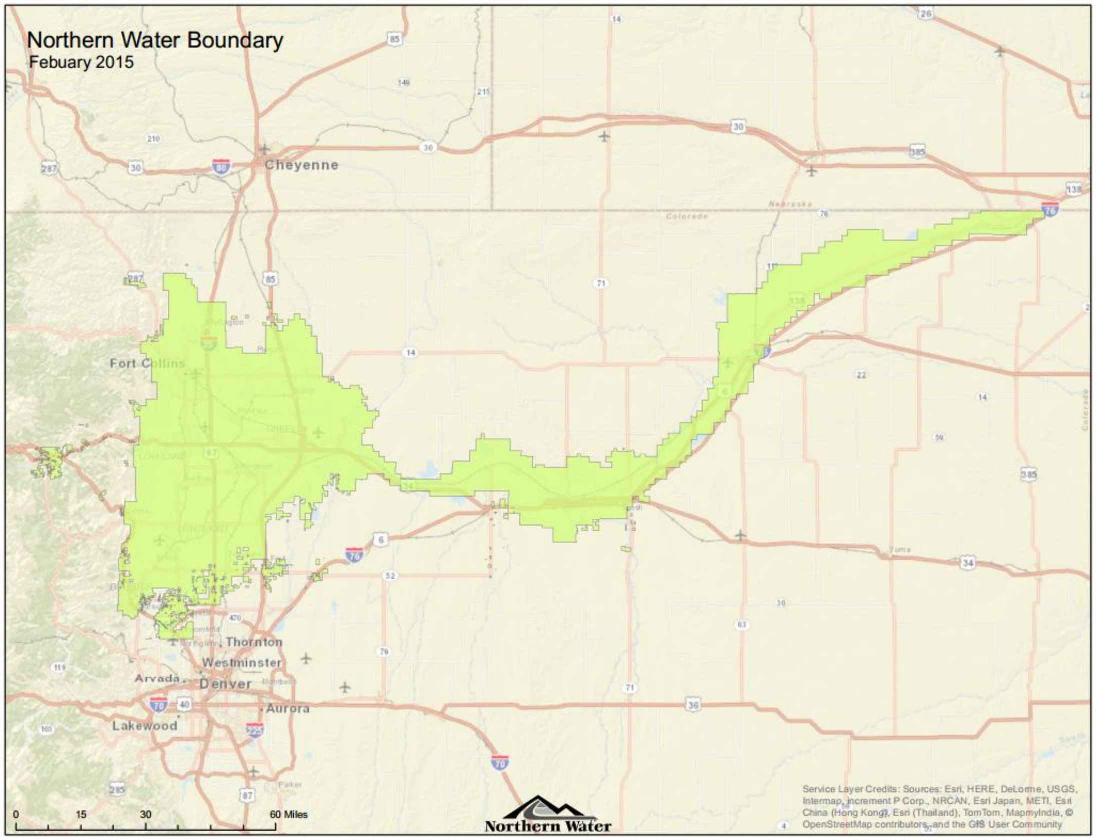
Some scholars would argue that in our modern technological age, growth is decoupled from resource availability. The well-known Cornucopian economist Julian Simon, states that in our modern age scarcity will cease to exist. Furthermore, he postulates, “Water does not pose a problem of physical scarcity or disappearance” (Simon & Kahn, 1984). Simon is not alone in his observation, as numerous scholars (Riebsame, 1997) have noted in Colorado and across the West, water availability does not appear to serve as a significant limiting factor for population growth management. Indeed, the founding of urban centers in the semi-arid climate of the Front Range seems superficially to invalidate these earlier predictions of intrinsic limits to the settlement of the region (Limerick, 2012). Yet in the Colorado, the fact that population growth has occurred despite limited water supplies does not prove that humans are independent from the constraints of their physical environment; rather, it suggests that explosive progress in science and technology “have loosened the iron grip of natural scarcity on human life” (Deudney, 1991).

In reality, the manipulation of the environment and water resources remains central to the viability of agriculture in the Rockies region today. The emergence of new water entities, innovative feats of engineering, and creative mechanisms for water “wheeling and dealing” have "produced an elaborate network of dams, reservoirs, tunnels, ditches, pipes, pumps, and filtering plants that [have] reconfigured the arrangements of water" and made possible the impossible in an improbable setting (Limerick, 2012). Perhaps no more remarkable example of this exists than in the Northern Colorado Water Conservancy District.

The Northern Colorado Water Conservancy District

The Northern Colorado Water Conservancy District (Northern Water) is a public agency created in 1937 in contract with the U.S. Bureau of Reclamation (formerly the U.S. Reclamation Service) to build the Colorado Big Thompson Project. After years of economic depression and devastating drought during the 1930s, farmers and influential business people in the Northern Front Range formed the Northern Colorado Water Users Association in 1935 in order to provide farmers with a reliable water supply. The Association proposed the Colorado Big Thompson Project "Big Tom" to divert water from the Fraser River west of the Continental Divide to the Front Range. In May 1937, the Colorado Legislature passed the Water Conservancy Act, which laid the legal framework to create Northern Water the same year (NCWCD Colorado Big-Thompson Project: 2014). After two decades, the Colorado Big Thompson Project was completed. Today, Northern Water encompasses 12 reservoirs, 35 miles of tunnels and 95 miles of canals. This extensive infrastructure collects and delivers more than 300,000 acre-feet of water, the majority of which comes from snowmelt in the upper Colorado River basin west of the Continental Divide.

Northern Water Boundary Map

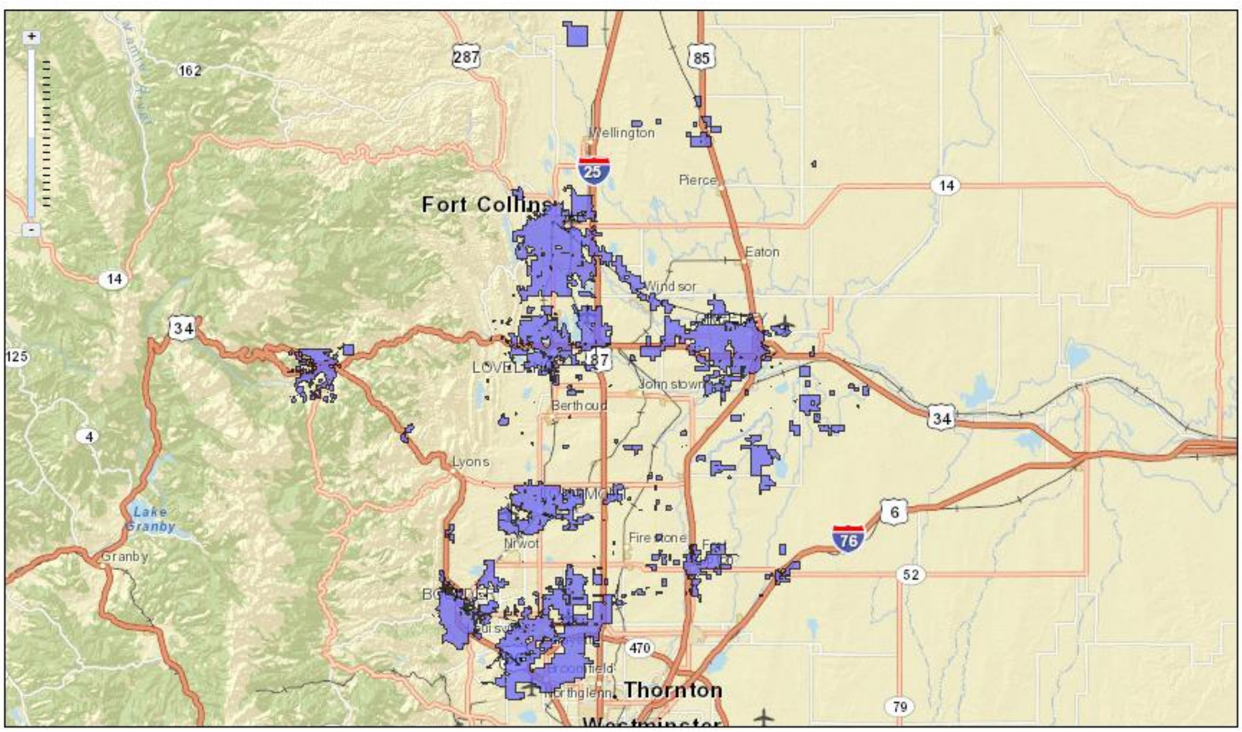


http://www.northernwater.org/docs/Water_Projects/PDFmapsWaterProjs/NWBoundaryPrint.pdf

When the Big Thompson project was completed in 1957, 97 percent of its water deliveries ensured a reliable source of **supplemental** irrigation water for Northeastern Colorado farmers (NCWCD the Colorado Big Thompson Project: 2014). These farmers and original shareholders in the project wanted to ensure that drought would never again devastate their lands and communities as it had done in the height of the Great Depression. Today, Northern Water continues to supplement the irrigation supply of farms within its boundaries, serving more than 640,000 acres of irrigated farm and ranch land. Yet only about one-third of the water delivered goes toward agriculture. As the region has become increasingly urbanized, the majority of the water now serves the approximately 860,000 people in portions of eight counties within Northern Water's 1.6 million acre boundaries (NCWCD the Colorado Big Thompson Project: 2014).

While originally designed as a supplemental agricultural supply, Northern now serves as an essential supplier for the cities of Estes Park, Fort Collins, Greeley, Loveland, Longmont, Boulder, Louisville, Lafayette and Broomfield. In 1967, several of these municipalities filed for water rights on the Colorado River in order to secure water for their rapidly growing urban centers in the Northern Front Range. The cities, which already resided in boundaries of Northern Water, formed a Municipal Subdistrict in 1970, with the same powers and legal standing as the parent Northern Water. After two decades, the Subdistrict completed its inaugural Windy Gap Project, which since 1985 has diverted 48,000 acre-feet of water annually. In terms of acre-feet delivered, and population served, Northern Water is the second largest water provider in Colorado.

Municipal Subdistrict Boundaries Map



http://www.northernwater.org/WaterProjects/SubDistrictBoundaries.aspx

Northern Water's Mandate and Goals

The mission statement of Northern Water is to "Provide water resources management, project operations, and conservation services for project beneficiaries" (Northern Water Strategic Plan, 2015). Northern Water operates as a trustee of water rights held by shareholders in its district and is tasked with managing water to maximize its beneficial use. Northern Water's Strategic Plan (Strategic Plan, 2015) outlines the conservancy district's five primary goals:

1. Deliver Water—"Efficiently and economically collect, convey, store, distribute, and administer water in a safe and reliable manner."
2. Conserve and Protect Water Supplies—"Conserve and protect water supply and monitor water quality using all appropriate operational, engineering, legal, and administrative measures."
3. Plan for Future Water Supplies—"Plan, permit, design, and construct projects to enhance, increase, and sustain water supplies for agricultural, domestic, municipal, and industrial uses in Northern Colorado."
4. Cultivate Organizational and Operational Excellence—"Cultivate and maintain a quality workforce, appropriate technology, facilities, and equipment, as well as effective operational policies, rules, and procedures."
5. Strengthen and Maintain Positive Relationships—"Develop, strengthen, and maintain cooperative, collaborative, professional relationships with beneficiaries, constituents, partners, stakeholders, government agencies, the conservation community, and the general public."

After eight decades, Northern Water remains one of the leading water providers in Colorado and maintains the largest transmountain diversion project in the state. Yet, in the face of population challenges, fulfilling its expressed mission and priorities is becoming increasingly complex. The Northern Colorado Water Conservancy District is not exempted from the impacts of population growth, and is in fact, poised to be at the epicenter. Nichols, Murphy, and Kenney (2001) quote former Attorney General of Colorado, Ken Salazar who stated that in the Front Range "Growth is going to come, no matter what." This statement is particularly true for the Northern Water District as the Colorado State Demography Office estimates that the 2015 population of Northern Water's service area—1,461,236—to reach at least 2,573,163 people by 2040 (Colorado State Demography Office, 2012). This represents a 76 percent increase under medium-growth models (2012). Past endeavors such as The Big Thompson and Windy Gap projects enabled Northern Water to meet growing demands. Today, there is concern about garnering enough new water to serve the increasing population, even if there is not a fundamental concern that water is currently scarce.

Implications of Population Growth

Although population growth in the Northern Front Range is not predicated solely upon the availability of water resources, it would be incorrect to assume that the two factors lack any type of relationship. Corbridge states bluntly in his article "Historical Water Use and The Protection of Vested Rights" that "population increases and finite supplies have combined to put an increased strain on Colorado's water resources" (Corbridge, 1998). Population growth in the Front Range corridor creates a higher demand for domestic water. Water agencies must provide for the ever-growing needs of their constituents, and they have responded by acquiring water rights from irrigated agricultural producers (Sutherland & Knapp, 1988). For example, between 1979 and 1999, hundreds of thousands of acre-feet of water transferred within Northern Water. Of these transfers, 64 percent were from agricultural to urban use (Howe & Goemans, 2003).

Consequently, the shifting of water rights has stirred up competition for water resources among different sectors of society. The level and scope of this competition varies greatly among Front Range water providers given their different infrastructures, population patterns, and water rights portfolios (Nichols, Murphy, & Kenney, 2001).

Colorado Water Law

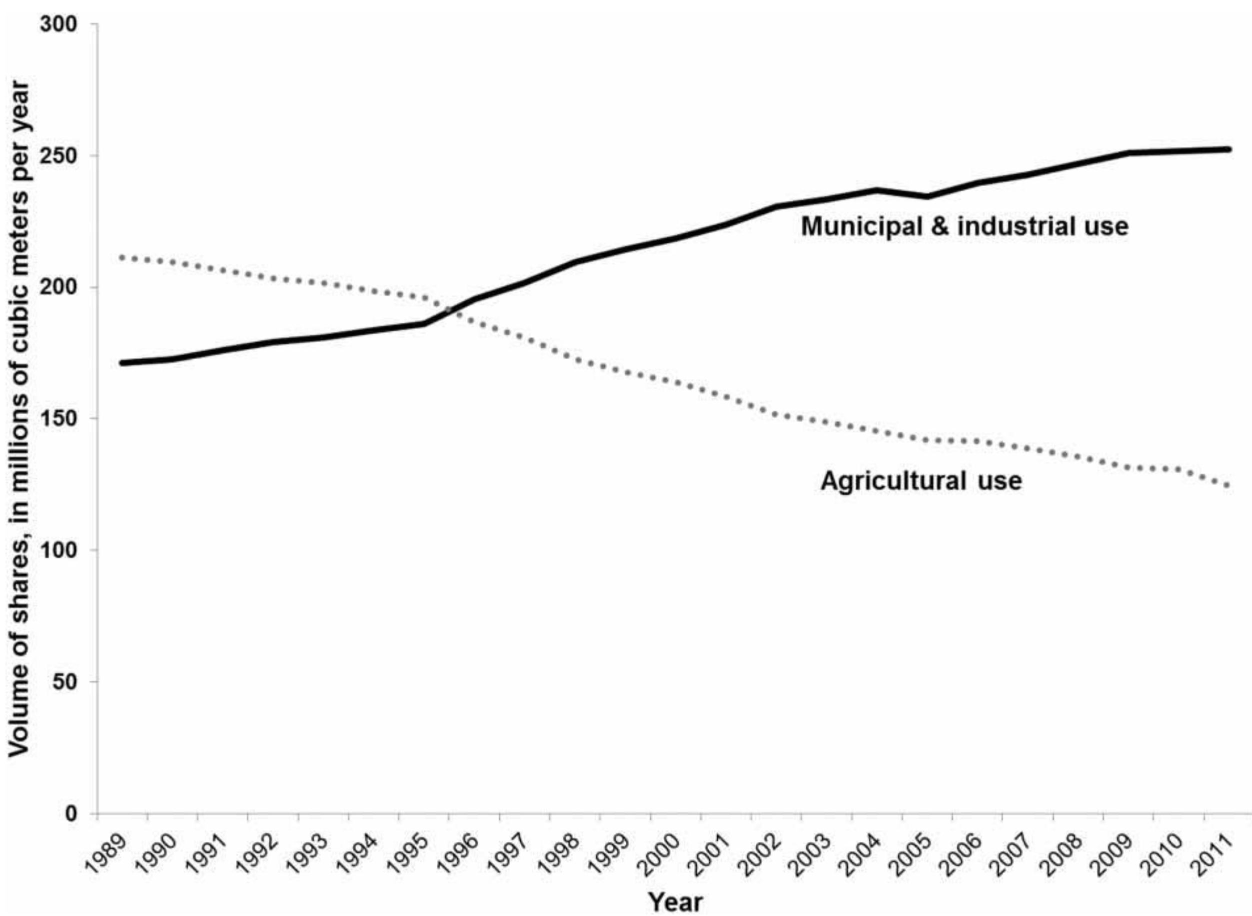
For the majority of water entities, “competition for water resources is associated legal and policy issues involving trans-basin diversions, environmental protection, water quality management, and interstate obligations” (Nichols, Murphy, & Kenney, 2001). Colorado’s law of prior appropriation generally allows for the diversion of water from one place to another without consideration of the geographical location. The first person or organization, or corporation to file a water right—putting the water from a stream or surface feature to beneficial use—becomes the senior appropriator in perpetuity (Jones & Cech, 2009). Under this system, water is a separate right from the land and can be sold, leased or transferred as pleased, though under the supervision of the water court. Given that the senior appropriator has the right to realize his or her rights to their fullest extent insofar as they are being utilized beneficially, the owner can use the rights wherever he or she please: to irrigate a hay meadow next to the stream from which the water is drawn, or to irrigate an urban lawn one thousand miles away. The prior appropriation doctrine remains the “essential mechanism for extending the reach of cities into their hinterlands and thus for raising the states of municipal power” to support their growth (Limerick, 2012).

While some of these features pose challenges for Northern Water, Northern is unique in the fact that no one can transfer water out of its boundaries due to financial and contractual obligations to the U.S. Bureau of Reclamation originating back with the Big Thompson Project (Howe & Goemans, 2003). Resultantly, the movement of water in Northern Water is almost exclusively intra-boundary; there is a generally fixed amount of water, a fixed geographic setting, and a growing number of consumers. Furthermore, one hundred percent of the Northern Water is already appropriated. The Northern Water system operates under quotas in which all allottees receive a proportion of their shares within the district boundaries. For example, in the Big Thompson Project, a 100 percent quota makes 310,000 acre-feet of water available. Each C-BT allottee receives one acre-foot of water for each unit owned. In drier years, the volume of water available to be delivered through the collection system is limited by the need to first satisfy higher priority rights. Under a 70 percent quota, each allottee receives 7/10 of an acre-foot per unit. Thus, an allottee who owns 100 C-BT units can receive 70 acre-feet of water (NCWCD: C-BT Project Quota, 2014).

Finally, while most water transfers must be filed before a water court, transfers within the conservancy district are subject only to approval by the Board of Directors (Howe & Goemans, 2003). The structure of Northern Water typically means that it boasts lower cost-of-transactions than other water basins, which incentivizes more frequent and flexible arrangements (Howe & Goemans, 2003). For Northern Water, the challenge is not preventing the outflow of its water resources to other basins, but rather importing new supply, balancing the new and existing supply among municipal, agricultural, and environmental sectors, and managing the impacts of water moving between them.

Water Transfers

Water transfers from agriculture to municipalities directly reduce agricultural production, resulting in a cascade of secondary economic and social consequences for the region. First, as the transfer of water rights from agricultural producers to municipal uses has been rising in recent years, so have water prices. Simply put, population increase has increased demand for water rights, and with limited supply, prices have responded predictably (Brown, 2006). As water rights have increased in price, it has become more appealing for additional farmers and ranchers sell their water rights to developers because the profit is often higher than many consecutive years of good crop yields (Peglar, 2000). The Denver Post described how in years of drought or poor commodity prices, water becomes the best, “most saleable crop” a farmer has (Gordon, 2012). The success of one deal often ripples through farming communities, bringing forward additional sellers who which to cash out their supply, resulting in serial transactions that rapidly change the availability of water in a particular area.



Changing ownership structure of permanent water rights in the Northern Colorado Water Conservancy District (Debaere, et al., 2014)

Impacts of Agricultural to Urban Water Transfers

When agricultural production decreases, those activities linked to the supply chains of production decrease accordingly (Rosegrant & Ringler, 1998). While sellers or leasers of water shares receive direct benefits in the form of economic compensation, producers leasing water shares face higher water prices, suppliers of agricultural equipment and seeds lose their customer base, financial institutions receive fewer loan applicants, and seasonal workers lose agricultural employment opportunities (Howe & Goemans, 2003). If agriculture based jobs are not replaced by other markets, increases in costs of operating as well as losses of income result in social displacements. Although not typically the case, the majority of Northern Front Range communities have gained new employment high-tech manufacturing, food processing, and energy production that replaces jobs lost in the agricultural sector (Howe & Goemans, 2003). In addition, the growth of nearby cities has provided remaining agricultural producers with markets and income that has fueled diversification into higher-value crops (Rosegrant & Ringler, 1998) (Howe & Goemans, 2003).

The sale and lease of senior, dependable agricultural water right shares to cities, golf courses, energy producers, or other new users within the Northern Water District also has critical natural resource and land use implications. Once water rights are removed from irrigated farmland, the alternative land uses remaining are rather limited, with croplands most often being left untended (Corbridge, 1998). Under such “buy and dry” scenarios, croplands are left fallow and the potential for soil erosion may increase if not properly managed, as natural precipitation cannot sustain vegetation at previous levels (Corbridge, 1998). A prime example of the devastation caused by buy and dry agricultural to municipal transfer tactics lies in the Arkansas Valley in Colorado’s southeastern plains. Between 1989 and 1999, the Rocky Ford Ditch—the canal with the most senior priority water rights on the Arkansas River sold 94 percent of its water to the City of Aurora, a Front Range city with a blossoming population (Gordon, 2012). Simultaneously, the Colorado Canal Company, which provided water for much of the same farmland, sold its water rights to Front Range municipalities. The result: the rapid and widespread loss of water in the region turned the farmland near Ordway Colorado into barren prairie characterized by dust storms and desertification.

In areas of low precipitation, conversion of irrigated cropland to rangeland through re-vegetation is the preferred solution to control soil erosion by wind and precipitation events. Unfortunately, re-vegetation attempts in the semi-arid shortgrass prairie of the Northern Front Range have been less that 50 percent successful (Sutherland & Knapp, 1988). With an average of only 14.5 inches of annual precipitation, native grasses are slow to reestablish on soils altered by years of sedimentation, nutrient depletion and high numbers of invasive weeds. Water transfers from agricultural to municipal users have the potential to produce long-term, detrimental effects upon soil condition and grassland composition, but despite their negative effects, agricultural-municipal transfers remain the status quo management strategy for meeting much of the foreseeable demand shifts. Maintaining the status quo could result in loss of agricultural lands, harm to ecosystems and recreation based economies, water-inefficient land use decisions, and continued paralysis on water supply projects. In addition, costs associated with the status quo could cost Colorado billions of additional dollars (SWSI, 2011).

Population growth has a visible and predictable impact on water demand in Northern Water; but other impact factors, including climate change and adaptive capacity will collectively determine the ability of Northern Water to meet their obligations during the next fifty years.

Climate Change Projections

Until recently, the extent of climate change impacts on Colorado's water supply was not well understood. Even as recently as 2011, the Statewide Water Supply Initiative (SWSI)—commissioned by the Colorado Water Conservation Board (CWCB) to serve as the foremost governing document for decision-makers—did not consider impacts of climate change on the state's water systems, but instead, suggested that "it be included in subsequent forecasting efforts" (CWCB, 2011). While water providers like Northern Water have been able to manage for the demands of a growing population, largely by transferring shares between sectors, the environmental effects of climate change are "considerably more problematic than traditional water supply concerns" (Miller & Rhodes, 1997**). Under current considerations—without accounting for the effects of climate change—Northern Water projects a 110,000 acre-feet water deficit by 2050 (NCWCD, 2012).**

Given that the total acre-feet capacity of Northern Water is 310,000 acre-feet, and the average annual amount delivered is 260,000 acre-feet the potential deficit is nearly one-third of the current total, and far from being negligible (Debaeres, et al., 2014). Although population affects water demand and distribution, population growth in itself does not directly undermine the water supply. In contrast, "even modest climatic changes have the potential to modify the amount and distribution of precipitation in the state, as well as influencing patterns of demand and use" (Nichols, Murphy, & Kenney, 2001). The implications of climate change on Colorado's water resources are broad, severe, and already being felt.

Recent academic efforts have provided new evidence that substantiates the hypothesized climate changes in Colorado. This research directly applies to the water resources managed by Northern Water. The Western Water Assessment (WWA) was established in 1999 at the

University of Colorado at Boulder as consortium of researchers to explore the present-day impacts of climate change on social vulnerability, water resources, and adaptive strategies (Fahlund, Choy, Szeptycki, 2014). In the last several years, The WWA has produced a number of new publications documenting observed climate variability in Colorado. Concerning historic observations, WWA's Report, "Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation" (Lukas, et al., 2014), describes that Colorado has experienced:

- An increased in statewide annual average temperature of 2.5 degrees Fahrenheit (°F) over the past 50 years
- A greater increase in daily minimum temperatures than daily maximum temperatures over the past 30 years
- Snowmelt and peak runoff periods 1-4 weeks earlier over the past 30 years due to a greater portion of winter precipitation falling as rain, warming spring temperatures and the effect of increased dust deposition on snow
- No long-term trends in average annual precipitation

The evidence is clear: Colorado's climate is currently linked to global trends. One such example is that as the frequency and severity of droughts in the entire West increase, vegetation levels decrease, subjecting the Colorado Basin and other arid regions to wind-driven erosion (Fahlund, Choy, Szeptycki, 2014). These wind-blown particulates from across the region deposit on the snowfields of the high peaks in Colorado, decreasing albedo, contributing to more rapid heating, and melting events (Lukas, et al., 2014). Like the rest of the planet, Colorado is warming, which affects the timing, form, and distribution of water resources across the state. In many watersheds, global climate change has already increased earlier peak runoff periods, reduced late-summer flows, and extended the growing season (Kenney et al., 2008). Although a longer growing season in the Northern Water District can present an economic opportunity for agricultural producers, it invariably increases the demand for irrigation water.

Climate change has become a known source of shifting environmental variability, but there is still a lack of recognition by decision makers and water rights owners on the impacts to the patterns of water availability in terms of total supply and quality (Lukas, et al., 2014). Most likely, the resistance to this data is that while the trends in terms of rising temperature and earlier runoff timing are rooted in years of historic records, the research describing the impacts to water quality and availability is new and relatively limited in terms of location and breadth. Regardless of the specific impacts, Northern Water needs to be prepared to address any number of changes brought by climatic shifts if it wishes to "Plan for Future Water Supplies" and "Conserve and Protect" the quality of its resources for a growing population in the future.

In consort with the current repercussions of climate change in Colorado, the literature points to a future characterized by increasingly acute disruptions to the natural water systems. Projections made for Colorado by Gordon and Ojima (2014), predict:

- "All climate model projections indicate substantial future warming in Colorado. The statewide average annual temperatures are projected to warm by 2.5°F to 5°F by 2050 relative to a 1971–2000 baseline under a medium-low emissions scenario. Under a high emissions scenario the projected warming is larger at mid-century (3.5°F to 6.5°F), and much larger later in the century as the two scenarios diverge" (Gordon & Ojima, 2014).
- Overall winter precipitation increases by the mid-21st century
- Winter snowpack decreases (Reiblich & Klein, 2014)

- Summer precipitation decreases, or occurs more erratically contributing to flooding events (Colby, et al., 2015) (Reiblich & Klein, 2014)
- Heat waves, droughts and wildfires are projected to generally increase in frequency and severity in Colorado by the mid-21st century due to the projected warming

Summarizing Climate Implications

With projected warmer temperatures, the Western United States, including Colorado, will face a series of challenges to maintaining reliable water supply that can meet demands for cities, farms, and ecosystems (Colby, 2015). Primarily, the increase in temperatures will affect the seasonal distribution and form of precipitation received, leading to less snow and more severe precipitation events. Secondly, increased temperatures initiate a positive feedback loop of evapotranspiration, which directly affect soil, surface water and ground water supply in both the short and long-term and contribute to droughts and wildfires (Reiblich & Klein, 2014). Third, as rates of evaporative loss increase, climate change will affect not only initial surface runoff into a stream system, but also seepage to groundwater aquifers, recharge from those aquifers and rates of consumptive use from irrigation withdrawals along the entire stream system (Miller & Rhodes, 1997). These shifts in water supply will indirectly affect those responsible for managing consumptive use and conveyance facilities (Miller & Rhodes, 1997). They are equally important to parties seeking to establish new water rights and to those interested in ensuring the preservation of aquatic systems.

In addition to affecting the quantity of available water resources, climate change threatens to undermine Northern Water’s capability to “conserve and protect” its water resources. With increases in temperature, lake water temperatures also increase, which can lead to blooms of organic matter (Gordon & Ojima, 2014). This can in turn spawn production of toxic byproducts that not only harm natural ecosystems, but also require more intensive disinfection processes that increase the cost of treatment and conveyance systems (Reiblich & Klein, 2014) (Gordon & Ojima, 2014). Finally, if warmer temperatures result in lower median flows due to sporadic events, concentrations of metals, sediments and nutrients will increase exponentially, potentially damaging irrigation equipment, contaminating food supply, and decreasing customer confidence (Gordon & Ojima, 2014) (Arrow et al., 1996). As if meeting the demands of a growing urban population already did not present enough of a formidable obstacle for Northern Water, population growth combined with the consequences of climate change certainly does. Addressing the projected supply shortage caused by population growth will be made more complex by the implications of climate change on Northern's water resources. In the upcoming decades, Northern Water will need to adapt its management decisions and actions to cope with the projected supply demand gap and ensure that it can fulfill its mission.

Adaptation

Traditionally applied by ecologists to the adaptation of a species under changing environmental conditions, climate scientists have offered an abundance of new definitions—and applications—for the adaptation framework within the climate change discourse. The Intergovernmental Panel on Climate Change defines adaptation as a process of adjustment to present-day and predicted climate effects that seeks to prevent or lessen the impact of harm (IPCC, 2014). Complementing the IPCC's theoretical perspective, Jamieson's definition (1997) analyzes adaptation as a function of time—responding to climate change in the present and in the future. Within this context, one can derive that climate adaptation is complex; it can be preventive or reactive, independent or coordinated, spontaneous or planned (Fankhauser et al., 1999). This paper utilizes the framework articulated by Adger, Arnell, and Tompkins (2005) in their article “Successful Adaptation to Climate Change Across Scales.” They define adaptation as,

> “An adjustment in ecological, social or economic systems in response to observed or expected changes in climatic stimuli and their effects and impacts in order to alleviate adverse impacts of change or take advantage of new opportunities. Adaptation can involve both building adaptive capacity thereby increasing the ability of individuals, groups, or organizations to adapt to changes, and implementing adaptation decisions, i.e. transforming that capacity into action. Both dimensions of adaptation can be implemented in preparation for or in response to impacts generated by a changing climate” (Adger, et al., 2005).

Keeping in mind that the natural and human systems are inextricably linked, this definition presents a potential solution to the problems presented by climate change in the Northern Front Range of Colorado. If Northern Water decides to take actions to ensure the security of water supply through demand management and behavior alteration, their actions can reduce the severity of threats to water resources by changes in climate and population. Not unsurprisingly barriers can hinder adaptive capacity building and prevent the implementation of adaptation decisions (Moser and Ekstrom, 2010). Identifying the barriers to adaptation and developing an understanding of how to overcome them is the chief goal of scientists who want to develop innovative solutions to climate’s complex social and ecological circumstances (Armitage, 2005).

Adaptation experts have utilized three main approaches through which adaptation occurs at municipal, regional, or even international levels: altering exposure, reducing sensitivity, and increasing resilience (Adger, et al., 2005). The method of altering exposure focuses on changing the environmental system; the sensitivity reduction approach focuses on strengthening relational networks and vision; the resilience approach centers on organizing a system to absorb and respond to shocks to human societies and ecological systems (Walker, et al., 2006) (Folke, et al., 2002).

Barriers to Adaptation

Moser & Ekstrom (2010), define barriers to adaptation as, “obstacles that can be overcome with concerted effort, creative management, change of thinking, prioritization, and related shifts in resources, land uses, institutions, etc.” In contrast to ecological limits that essentially are insurmountable in a given context, barriers are considered flexible based on the capacities of actors, the larger context in which they act, and the characteristics of the object upon which they are acting (Adger, et al., 2005). For application in this thesis, the actors correspond to the governing body of Northern Water—the Board of Directors—and their shareholders, the context for action is the Northern Colorado Water Conservancy District Boundaries, and the object of action is Northern Water’s water resources.

The structure for understanding potential barriers to adaptation is proposed by Moser & Ekstrom (2010) in “A Framework to Diagnose Barriers to Climate Change Adaptation.” The framework involves a breakdown of the adaptation process to climate change into three stages: understanding, planning, and management, and an analysis of the various obstacles that can emerge during each period. The first stage, adaptive understanding, involves barriers to problem detection, knowledge collection, and problem definition. Problem detection can be missed or suppressed when the actor is too distant from the signal to take note, or if actors are distracted by another more-pressing need. Additionally, an issue may not reach the “threshold of concern” that serves as the impetus for taking action because the consequences of an issue are uncertain. The second stage of the model involves barriers to adaptive planning. During the development of adaptation options, assessment of options, and selection of options actors' biases can cause them to ignore potential solutions or they may focus their deliberations only on options they perceive to be under their control (Moser & Ekstrom, 2010). The third and final management phase contains barriers to adaptive management, which includes the implementation of the selected option or options, monitoring of the outcome of these actions and the evaluation of the results in order to inform future adaptation decisions (Moser & Ekstrom, 2010). The most significant barriers to adaptive management revolve around limited availability of human, social, and technological resources (Moser & Ekstrom, 2010).

Adaptive Capacity

Responding to climate change will involve tackling the aforementioned barriers through the building of adaptive capacity, defined as the ability of Northern Water to adjust its structural and behavioral practices in order to better manage for existing and future stressors of population and climate (Morss, et al., 2011). Yohe & Tol (2002), offer an expansive list of adaptive capacity determinants. These include: 1) technological options; 2) availability of resources and their distribution across the population; 3) the structure of critical institutions and the allocation of decision-making authority; 4) human capital; 5)social capital; 6) risk spreading; 7) ability, legitimacy and transparency of decision-makers; and 8) public perception of the source of stress. In general, the results of adaptive capacity studies have supported this broader set of determinants, as the influence of each determinant of capacity is highly dependent on human components in addition to institutional ones. Equally important in identifying the determinants of adaptive capacity is recognizing how they function. Factors that build adaptive capacity in some areas of the Northern Water District may also concurrently hinder adaptive capacity in other areas (Cutter et al., 2008). For example, isolating and altering one component of the system may result in no overall change, or may result in a cascade of changes, with both desired and undesired results. Although all the necessary determinants of adaptive capacity may be present in Northern Water, its ability to adapt may be affected by limitations in resources, institutional capabilities, and human attitudes and behaviors toward risk.

Water providers throughout the West, including Northern have a long history of implementing technical solutions to change their environmental exposure. In the 19^{th} and 20^{th} centuries, there was little hesitation by Northern Water and the Bureau of Reclamation to move water from remote locations in Colorado to places of agricultural production through complex engineering schemes. Patty Limerick, in her book *A Ditch in Time*, highlights, “this vision produced an elaborate network of dams, reservoirs, tunnels, ditches, pipes, pumps, and filtering plants that reconfigured the arrangements of water” (Limerick, 2012). The ability to implement technical solutions such as these is an important form of adaptive capacity. Reservoirs, water diversions and artificial storage have allowed Northern Water to cope with extremes and help shield human activities from the variability of the water resource. While effective as a “prediction-and-control approach” (Pahl-Wostl, 2007) with an emphasis on technical solutions, the uncertainties presented by climate change demand the integration of additional forms of adaptive capacity into Northern Water’s repertoire. Two methods for reducing sensitivity and increasing adaptive capacity involve the strengthening of Northern Water’s social capital networks and adherence to the strategic planning process.

Social Capital and Networks

The speed with which a community can mobilize and use resources to spread climate risks such as drought, disease, or rising sea levels is strongly dependent on the strength of its social networks (Magsino, 2009). Janssen, et al. (2006) defines social networks within the adaptive capacity field as comprised of "nodes and links" that represent actors and relationships; the number of nodes and number of connection determines the resistance to the flow of information or materials between actors.

Networks appear to promote adaptive capacity through at least two distinct ways: 1) networks foster coordination, communication and shared knowledge between stakeholders, increasing their ability to cope with variability and change, and 2) networks concentrate the influence of individuals within groups who are more visible and capable of making policy or social decisions (Bierbaum et.al, 2013) (Tompkins & Adger, 2004). The assumption of the network is that actors are mutually dependent on the resources controlled by each other (Machado, et al., 2002). In pooling these resources, members of the network increase their level of connectivity (the density of their links to one another) and their reachability (the extent of accessibility) Janssen, et al. (2006). Accessibility is inherently related to transparency, and transparency, legitimacy (Newell, 2008). In effect, social networks can address many of the barriers to adaptation through information sharing, networks link science with policy, reducing conflicting objectives (Tompkins & Adger, 2004). Social networks produce synergistic outcomes that work through communication and legitimacy barriers and favor adaptive capacity building.

One of Northern Water's organizational priorities is to "develop, strengthen, and maintain cooperative, collaborative, professional relationships with beneficiaries, constituents, partners, stakeholders, government agencies, the conservation community, and the general public" (Northern Water Strategic Plan, 2015). In recognizing that collaborative social networks are a critical component of any management strategy, the Northern Water Board of Directors has laid the foundation for adaptive capacity building surrounding water in their region because these social interactions speed up social learning and increase adaptive capacity. Furthermore, considered alone as an organization, Northern Water meets Machado's definition of a social network in which members are mutually dependent on the resources that they share (Machado, 2002). In the Northern Water structure, each of its allottees shares a portion of the total resources. Because 100 percent of available water is allocated between shareholders, one actor's use of water necessarily affects the ability of another to utilize his or her water. Consequently, all actors in the network feel changes to management decisions swiftly and clearly. This facilitates the flow of information and combats social fragmentation.

Strategic Planning

Strategic planning is a common adaptive capacity building practice to reduce sensitivity to climate threats because it facilitates a systematic form of preparing for change in the present and in the future. Specifically, strategic planning builds on the knowledge from social network participation because it depends on information about opportunities and constraints for a given area (Palazzo & Steiner, 2011). As Steinberg states, strategic planning "establishes the basis for joint actions of all relevant stakeholders for a defined period of time. It identifies a long-term vision, takes into the socioeconomic and environmental context, identifies competitive advantages, concentrates on critical issues, and establishes an integrated strategy" (2003). Planning outcomes that build adaptive capacity recognize that reciprocal relationship of organisms to one another and to their biological and physical environments (Palazzo & Steiner, 2011). They involve shifting land use and modifying natural resource management through a number of methods including increasing reservoir storage capacity, planting hardier crops that can withstand more climate variability, or simply as ensuring that buildings in known flood plains or coastal areas are constructed with a floodable ground floor (Adger, et al., 2005). Without an integrative viewpoint, social capital erodes, yet with comprehensive planning, the interdependence of human and natural systems is recognized and uniquely tailored to adapt to a variety of circumstances.

Developing the will and capacity for individuals and organizations to engage in long-term, collective action is fundamental before that action can take place. Northern Water's resource management actions are guided by its Strategic Plan, a document created by its Board of Directors, and found on its organizational website. Of Northern Water's five priorities, one priority is to "Plan, permit, design, and construct projects to enhance, increase, and sustain water supplies for agricultural, domestic, municipal, and industrial uses in Northern Colorado" (Northern Water Strategic Plan, 2015). Moser and Ekstrom (2010), in their article "A Framework to Diagnose Barriers to Climate Change Adaptation," cite Grothmann and Patt (2005) who find that the primary barrier to the management phase of adaptation is developing an actual "intent to implement" among the involved parties.

The fact that Northern Water has Strategic Plan is a significant because the plan represents that Board leadership is not merely undertaking coping mechanisms for water resource challenges in the short run, but has the intent to make long-term adjustments. Furthermore, the Strategic Plan clearly articulates the desired outcomes of the management process: *to enhance, increase and sustain water supplies*. These three key goals create a strong collective vision for Northern Water's leadership and shareholders, placing it in position to pursue new systematic transformations that necessary to address the long-term of impacts of the factors of population growth and climate change.

Implementing Adaptation Decisions—Adaptive Management

In the article “Stationarity is Dead” by Milly et al. (2008), the authors refute natural resource managers’ long-held assumption that natural systems oscillate within a predictable range for which a singular system design can control. Throughout the course of the last century, water management predictions have been based on the analysis of current and historical records, and scientists, planner, engineers, and policy-makers have relied on this data to make decisions about the future of water resources (Milly et al., 2008). Concerning the influence of stationarity and water management, Fahlund, Choy, and Szeptycki assert,

> “The West’s dams, levees, and other infrastructure, once the envy of the water world, were built on past assumptions. Laws and policies on water rights, species recovery plans, and clean water permits are calibrated to data collected over the last century, for the most part. Land use decisions are dependent on that data and history as well. The realization that the future will not conform to the past is now leading to a transformation in the water industry and a whole new way of thinking and working” (Fahlund, Choy, Szeptycki, 2014).

Population growth and climate change demand that water providers adjust the way that they plan for water resources in the future. Meeting this demand involves sweeping revisions to attitudes and tactics.

As Northern Water looks to plan for the future while providing appropriate returns to its shareholders in accordance with its mission statement and priorities, it will need to move from a prediction-and-control approach of its water resources to a management approach that increases adaptive capacities and ensures operation under a wide variety of conditions (Pahl-Wostl, 2007). **This systematic commitment to adjust to changing conditions, learn from outcomes, and constantly redesign management policies and practices is known as adaptive management** (Limerick, 2012). It is widely acknowledged in the literature that, in order to effectively manage for climate change, solutions need to be implemented across many societal scales (Selman, 2010) (Adger, et al., 2005). Adapting to climate change involves making decisions across a landscape made up of agents from individuals, firms and civil society, to public bodies and governments at local, regional and national levels (Adger, et al., 2005). Strategies for adaptive management in Northern Water can involve policy-makers and pushes for changes in laws and regulations on behalf of citizens (Lebel, et al., 2006). Conversely, Northern Water and its shareholders can become more adaptive to climate change through building adaptive capacity and implementing operational adaptation decisions at an institutional and individual level (Nyamwanza, 2012).

The most effective form of adaptive management decision making and implementation employs management programs that are designed to experimentally compare selected policies or practices, by evaluating alternatives for the system being managed (Pahl-Wostl, 2007). First, the ability to consider various scenarios gives policy makers the opportunity to try out alternatives that they might otherwise never consider. In three environmental resource management case studies examined by McLain and Lee (1996), they discovered that alternatives allow actors an opportunity to explore different "what if" scenarios. Second, while the authors criticize adaptive management for sometimes advocating for linear systems of thinking, they simultaneously commend the approach for identifying—when strong social networks are present—the kinds of institutional structures and processes that are needed for various management alternatives for their given resource. Third, the use of alternative analysis during the implementation of adaptive management actions mirrors the scientific process of hypothesis testing (Pahl-Wostl, 2007). Alternative analysis produces data that are replicable and results that are repeatable.

Alternatives for Northern Water

Faced with a critical 110,000 acre-feet supply-demand gap and increasing uncertainty of water timing, quality, and availability, this thesis explores several adaptive management alternatives available to Northern Water including: 1) alternative water transfers (AWTs); 2) firming of water rights through the construction of new storage projects; 3) conservation practices, and 4) graywater reuse. The exploration and analysis of these specific alternatives certainly capture only a fraction of the possible alternatives available to Northern Water; however, the selected alternatives represent salient options across array of designs, actors, scopes, and scales, and are well representative of the adaptive water management literature.

Alternative A: Alternative Water Transfers

In Colorado, cities have typically used 20% of total water available, while agriculture has used 80% (Limerick, 2012). In light of growing populations, urban demand for water will, and already has, shifted this distribution. In fact, water transfers from agricultural irrigation to municipal users have been the primary management strategy for meeting short-term discrepancies in supply and demand for water resources, and have decreased the number of irrigated acres in the state by over 200,000 in the last half-century (Western Resource Advocates, 2011). Many rural communities and agricultural producers view the loss of this water as a threat to their viability and their culture because of the potential negative environmental and economic consequences associated with permanent dry-up of agricultural lands. However alternative water transfers—or alternative transfer methods—include a number of legal, financial, and land-use arrangements between irrigation water rights holders, which attempt to balance competing urban and agricultural demands.

Alternative water transfer strategies include rotational fallowing, interruptible supply agreements, rotational crop management/fallowing agreements, water banks, alternative crops, deficit irrigation, and purchase and lease-back agreements (CWCB, 2012). In Colorado, interruptible supply agreements establish a ten-year payment schedule between municipal water providers and agricultural water rights holders. Municipal users pay the irrigation rights holder an annual fee, but in drought years, pay an additional premium to borrow the water rights pertaining to the contract (Mclane & Dingess, 2014). Interruptible supply agreements are approved by the State Engineer, limited to three years out of ten and may be renewed up to two times under Colorado Law. Rotational crop management—or fallowing—agreements, permit a farmer to lease a portion of their irrigation water rights to a municipal user in exchange for leaving a portion of the land fallow.

Water banks, first implemented in Colorado in 2003, allow the state engineer to develop rules for the governance of water resources that can be traded within individual water divisions. Water banks are designed to create markets that temporarily lease surplus water resources between users without risking permanent abandonment of these water rights or permanent transfer from the lands with which they are associated (Colorado College, 2011). Alternative crop and deficit agreements conserve water through planting less water-intensive produce or through reduced irrigation of existing crop types and allow the farmer to sell any water that is leftover to urban areas (Colorado College, 2011). Purchase and lease back allows municipal water providers to buy land from a farmer and thusly buy the associated water rights, or a portion thereof. If the farmer needs the land back, he or she can lease it from the city for a predetermined rate (Colorado College, 2011).

While these many alternative water management options are promising for implementation in Northern Water, there remain significant legal, financial, and reliability barriers. In the article, “Evaluating Crop Water Stress under Limited Irrigation Practices”, (Taghvaeian, et al., 2014) provides an overview of the inhibiting factors associated with alternative water transfers. These factors are substantiated by the literature:

- Lack of Deliverability Capability
- Administration and Accounting issues (SWSI, 2011) (Donovan, et al., 2014)
- High Transaction Costs and Mitigation (SWSI, 2011) (Western Resource Advocates, 2011)
- Risk and Uncertainty of Supply (SWSI, 2011) (Western Resource Advocates, 2011)

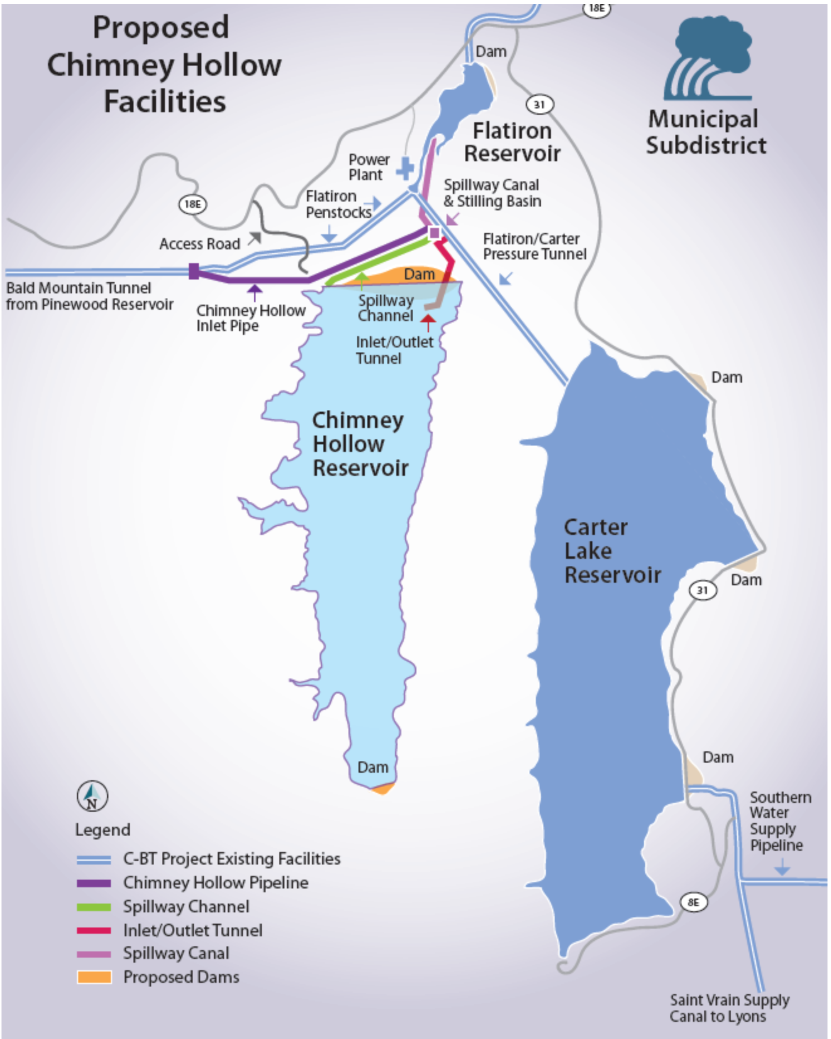
Given the novel nature of alternative water transfers and legal, financial, and structural challenges, they have not traditionally played a significant role in the of water management strategies. Complicating the acceptance of alternative water transfers is the variability of their cost. Given the market nature of water transfers, prices shift considerably in accordance with climatic trends, large transfers by water providers, and the availability of water in a given water district, division, or basin. Over a five-year period from 2005-2009, Kenney, et al., 2010, averaged the average cost per acre-foot for water from water transfers across Colorado. The study yielded the result that water transfers cost approximately $14,000 per acre-foot (Kenney, et al., 2010). Additional studies have focused on the cost of alternative water transfers and found significantly higher prices. In 2011, the State Water Supply Initiative estimated a range of

$33,500 per acre-foot to approximately $34,000 for alternative water transfers (SWSI, 2011). If the necessary infrastructure and agreements were in place, reports estimate conservatively that approximately 120,000 acre-feet of water transfers in the Front Range will be annually available by 2050, with 73,000 acre-feet of this supply available from the Big-Thompson Project for redistribution within the same district (Western Resource Advocates, 2011).

Alternative B: Firming Existing Water Rights through Storage

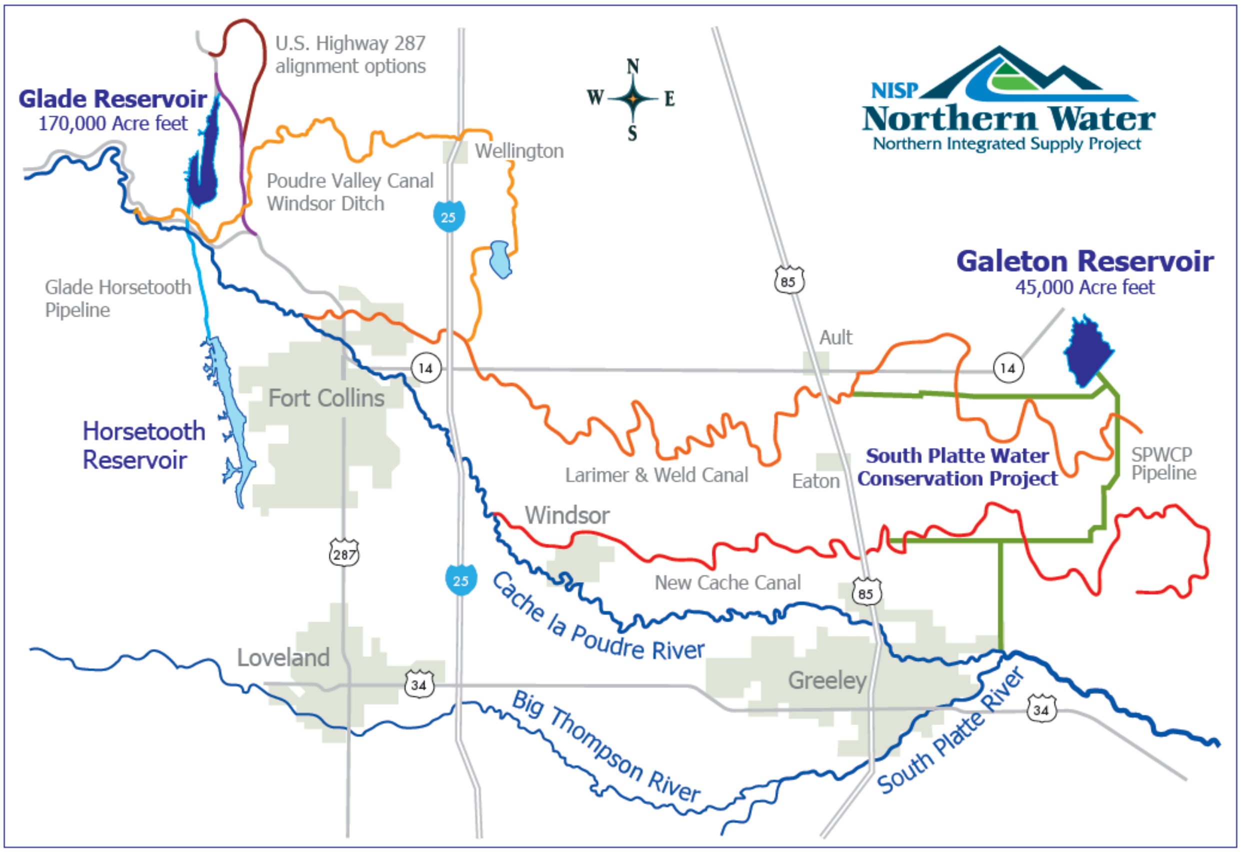
Population growth within Northern Water boundaries continues to increase demand for water. While the predominant short-term solution for meeting increasing demand—water transfers—has expanded supplies, Northern Water is looking toward new water supply projects that firm—or utilize fully—existing water rights through the construction of three new reservoirs under two new projects, the Windy Gap Firming Project and the Northern Integrated Supply Project (NISP).

The Windy Gap Firming Project is a collaborative undertaking by thirteen Northeastern Colorado Water providers to improve the reliability of, or firm, existing water rights. Begun in 2003, and scheduled to on-line by 2011, the Windy Gap Firming Project remained mired in regulatory delays until December 2014 when it received a final record of decision in support of the project from the Bureau of Reclamation. The project includes building the new 90,000 acre-feet Chimney Hollow Reservoir in the foothills west of Loveland, Colorado and adjacent to the existing Carter Lake Reservoir. Using the original Windy Gap water rights decrees from the 1985, water from the Windy Gap Reservoir will be diverted through the Alva B. Adams tunnel to the new reservoir. The project is expected to serve an additional 60,000 households annually by providing approximately 32,000 acre-feet per year in potential yield (NCWCD, 2014 "Windy Gap Firming Project") (Western Resource Advocates, 2011).



Map from (NCWCD, 2014 “Windy Gap Firming Project”)

As of 2013, Northern has spent more than $12 million in permitting alone, with the estimated total project cost increasing from $223 million to $285 million. Per household served, the project already costs approximately $1,033 dollars (NCWCD, 2014 “Windy Gap Firming Project”).The delay and cost of the Windy Gap project is not exceptional, particularly within the state of Colorado. In 1990, Denver Water’s $1 billion Two-Forks Dam project was derailed after years of litigation with environmental and citizen groups. Despite reaching the Final Environmental Impact Statement (FEIS) stage, the EPA vetoed the project due to concerns about water quality and endangered species. As Patty Limerick remarks in her book, *A Ditch in Time*, "The Two Forks veto is a crucial reminder that historical change is rarely a matter of linear progression or 'more of the same,' and far more a demonstration that contingency and choice interrupt and redirect seemingly well-established trends" (Limerick, 2012).



Map from (NCWCD, 2014 "NISP Overview")

Similarly, the Northern Integrated Supply Project (NISP) is being undertaken by Northern Water, to provide water for fifteen growing municipalities in the eastern portion of the Northern Water District whose populations are expected to double by 2050 (NCWCD, 2014 "NISP Overview"). NISP will result in the construction of two new reservoirs—Glade and Galeton Reservoirs—to lessen dependency on water transfers, alternative or otherwise, from agricultural uses. Glade Reservoir would divert water from the Poudre River during high flow seasons using junior water rights obtained by Northern Water in 1980 that have not been fully utilized (NCWCD, 2014 “NISP Overview”). Glade Reservoir would be slightly larger than the existing Horsetooth Reservoir at 170,000 acre-feet capacity and require the relocation of U.S. Highway (NCWCD, 2014 “NISP Overview”). Galeton Reservoir would be located on the plains northeast of Greeley, Colorado. Galeton would be operated by Northern as an integrated reservoir, relying upon the acquisition of new water rights and subsequent diversion from the South Platte Water Conservation. At 45,000 acre-feet, Galeton would be smaller than Glade Reservoir, acting to ensure that downstream users would not be impacted by additional water diversions from the Poudre River into Glade Reservoir (NCWCD, 2014 “NISP Overview”). Currently in the Environmental Impact Statement (EIS) process, a Draft EIS was released in 2014, with a final EIS planned for 2015, and a permit decision planned for 2016.

The proposed water firming and new storage projects have the potential to supply Northern Water with 40,000 acre-feet of water annually, yet the costs associated with building the project are substantial (Windy Gap FEIS, 2011). The traditional purpose of reservoirs has been to capture excess runoff in large volumes at infrequent intervals, in order to serve as a buffer against changing climatic conditions. In many ways, this approach to build the biggest dams possible has been successful, as the 2001-2002 severe drought demonstrated. However, the scale and infrastructure of new reservoirs and pipelines are significant. Kenney, et al., 2010 provides estimates for the average cost of water produced from storage projects at approximately $16,200 per acre-foot. Additional studies estimate a range of $28,600-$32,200 for new supply and storage development projects involving transfers on the Eastern Slope of the Continental Divide (SWSI, 2011).

Alternative C: Conservation Methods

Traditionally, water providers have relied on supply-side management as the preferred method for balancing the long-term supply and demand for water within their jurisdiction. In alignment with this model, Northern Water has planned to meet the projected supply-demand gap through water transfers and the Windy Gap and NISP supply and storage expansion projects. Yet in recent decades, a number of factors—growing populations, water resource constraints and uncertainty, and environmental regulations—have limited the ability of water providers to expand supplies and storage at sufficient rates to avoid projected water shortages (Halich & Stephenson, 2009). Consequently, there is growing interest among researchers, decisions-makers, and water providers in the efficient use of existing water resources, frequently called water conservation.

Baumann, et al. (1984) in their article "Water conservation: The struggle over definition," define water conservation as: "Any beneficial reduction in water use or in water losses, where…a reduction in water use occurs when a water management practice results in less water use as compared to the level of water use expected in the absence of the practice." This definition is fundamental because it specifics that not only must water conservation practices increase water efficiency, the practices must also decrease total amount of water used as compared to a no-action strategy. While conservation does not increase total amounts of water used, existing supplies are stretched, acting as a "new" water resource.

In Colorado, agricultural irrigation accounts for more than 80 percent of total water supply (Colorado College, 2011). In Northern Water, which has become highly urbanized, agricultural use accounts for only about one-third of the consumptive use today (NCWCD Colorado Big Thompson Project, 2014). Despite being a lesser destination for water in the district, agricultural irrigation still has a large impact on the success of water conservation goals. Irrigation techniques include flood irrigation, pressurized irrigation sprinklers, and low-flow drip, trickle and micro-sprinklers. Flood irrigation, which conveys water through open ditches and pipelines, is the dominant irrigation method, although it is only 40-65 percent efficient, as the majority of the water is lost to evaporation (Colorado College, 2011). Pressurized sprinklers provide an efficiency rate of 75 percent and low-flow systems boast efficiency rates of 90-95 percent, yet these systems are not readily accepted in areas without system requirements. Increased cost for infrastructure, as well as Colorado's prior appropriation system of Water Law, makes it difficult for agricultural producers to claim irrigation savings as a beneficial use, and thus poses an abandonment threat for their water rights (Wescoat, Jr., 1985).

For municipal water providers, two of the most commonly used approaches to reduce water use during times of scarcity are restriction programs (Halich & Stephenson, 2009). Both restriction approaches discourage certain water applications. Yet, in numerous studies, voluntary restrictions have been found ineffective; enacting water restrictions without enforcement mechanisms typically results in negligible savings (Halich & Stephenson, 2009) (Kenney, et al., 2004). In contrast, mandatory restrictions have been proven quite effective. Kenney, et al., (2004) studied the savings of water conservation approaches utilized by eight municipal water providers during the 2000-2002 drought in Colorado. Water savings were measured as a comparison of actual 2002 water usage levels versus those estimated from past trends and similar climatic conditions. The mandatory water restriction programs resulted in net use reductions of 13 to 53 percent during a four-month study period (Kenney, et al., 2004).

Utilizing the trends observed in the data from the water suppliers included in the study, potential water savings were extrapolated across four-months. For the municipalities studied along the Colorado Front Range, with a total combined population estimate of 1,851, 127, a medium mandatory reduction could result in savings of 32,491 to 48,998 acre feet (Kenney, et al., 2004). If these same providers were to implement more aggressive, mandatory water restriction strategies limiting outdoor watering to once per week, this would have translated into 113,920-130,301 acre-feet of savings in four months (Kenney, et al., 2004). Given that the estimated number of municipal users in Northern Water will be more than 1.5 million by 2050, the results of the mandatory water restrictions study show significant potential for conservation at a similar scale (Colorado Department of Local Affairs, 2012). Under extreme conditions, conservation has the potential to close the 110,000 acre-feet projected supply-demand gap projected for 2050 in Northern Water. However, for the purposes of this study, the medium savings scenario will be used to calculate the effectiveness, as it is more reflective of an acceptable, more practiced alternative.

Outside of water restrictions, dozens of water conservation strategies exist to curb water demand, including new construction standards, efficiency fixture requirements, landscaping guidelines, and budget-based rate structures. Water management entities, like Northern Water, can greatly influence total water demand by implementing a number of best management practices that remain as permanent conservation fixtures. At present, only 60 percent of the municipalities served in Northern Water's boundaries have conservation programs, so there is great potential to increase conservation efforts (Northern Water Conservation and Management Plan, 2011). The Guidebook of Best Practices for Municipal Water Conservation in Colorado (2010) identifies an extensive list of management practices, summarized in Table 3-3. The literature demonstrates that overall residential demand—indoor and outdoor—can immediately be reduced by an average of 40% as a result of installing more efficient appliances and fixture and low water landscapes (U.S. Environmental Protection Agency. 2005). In addition to being effective, these conservation practices present a significantly cheaper option than transfer and storage projects. In 2011, the Colorado Water Conservation Board estimated that a suite of conservation measures would cost on average, $10,600 per acre-foot to adopt (SWSI, 2011). Additional studies have shown that this average cost for water savings exceeding 300,000 acre-feet would be between $5,200-$11,098 per acre-foot (in 2010 dollars) (Kenney, et al., 2010).

Table 3-3: Complete package of best practices

No.	Best Practice	Comments
1-6	Suite 1	Metering and rates, IRP, water loss control, conservation coordinator, water waste ordinance, and public information and education.
8, 9, 11	Suite 2	Regulatory measures for new construction, new landscape, and redevelopment of existing landscapes.
7	Landscape water budgets, information, and customer feedback	Landscape water budgets address landscape water use and encourage efficiency. Comparing actual metered consumption against the legitimate outdoor water needs of the customer based on landscape area, plant materials, and climate conditions, provides powerful information about the irrigation practices and efficiency at the property.
10	Irrigation efficiency evaluations	The efficiency of an irrigation system can greatly impact the amount of water that is used in the landscape. Over time, even a well designed and properly installed irrigation system becomes less efficient unless it is well maintained and operated for maximum efficiency. This best practice describes key considerations for maximizing water efficiency through the use of regular irrigation efficiency evaluations.
12	High-efficiency fixture and appliance replacement for residential and non-residential sectors	The goal of this best practice is to increase the installation rate of water efficient fixtures and appliances and to remove inefficient and wasteful devices from the service area in favor of efficient products.
13	Residential water surveys and evaluations, targeted at high demand customers	Water surveys and evaluations (frequently referred to as "audits") that identify water savings opportunities and educate customers are a fundamental component of residential water conservation programs. Although often offered to all customers, high volume customers should be targeted first to maximize water savings and minimize program expenses.
14	Specialized non-residential surveys, audits, and equipment efficiency improvements	Specialized non-residential surveys and equipment efficiency improvements reduce water demands in the commercial, institutional and industrial (CII) sector. This best practice specifically *excludes* toilets, showers, and faucets (i.e. fixtures found in residential and non-residential accounts); however part of the survey process involves identifying all domestic fixtures that should be upgraded to improve efficiency.

Table from: Colorado WaterWise and Aquacraft, Inc. (2010). Guidebook of Best Practices for Municipal Water Conservation in Colorado. Denver, CO.

Alternative D: Graywater Reuse

Projects facilitating the reuse of graywater to augment supply along Colorado's Front Range have become an increasingly attractive and viable alternative water management solution to meet the 110,000 acre-foot supply-demand gap projected for Northern Water. Western Resource Advocates defines water reuse as "any arrangement that utilizes legally reusable municipal return flows to increase municipal water supplies," with return flows defined as "water that returns to a river after being treated at a wastewater treatment plant or to alluvial aquifers via percolation" (Western Resource Advocates, 2011). Graywater reuse allows some of the growing water demands to be met by existing supplies. The growing sources of demand are now satisfied from treated effluent rights that were previously "lost" from the water system when they were released back into streams. Graywater reuse effectively expands the existing surface water supply system without the acquirement of additional water rights.

Given Colorado's prior appropriation system of water allocation, water available for graywater treatment and reuse is limited to transbasin water that is imported from other tributaries or to exchanges between water rights holders in which a junior holder gives a senior holder expressed permission to reuse effluent in exchange for an equivalent amount of water (Mathieu, 1999). Any proposal to make use of effluent, or graywater in Colorado must consider whether diversion alters patterns of use, return flow patterns, or legally injures the rights of third parties (Wescoat, 1985). Regarding transbasin water reuse, Article 82, *Appropriation and Use of Water*, of the Colorado Revised Statutes, states:

> "37-82-106. Right to reuse of imported water—(1) Whenever an appropriator has lawfully introduced foreign water into a stream system from an unconnected stream system, such appropriator may make a succession of uses of such water by exchange or

> otherwise to the extent that its volume can be distinguished from the volume of streams into which it is introduced. Nothing in this section shall be construed to impair or diminish any water right which has become vested." (Mathieu, 1999).

Gray water—or effluent—reuse plans involve treatment of wastewater to a point where it is safe for consumptive use. These consumptive uses can range from household tap water, irrigation of parks, golf courses, and other public areas to the operation of hydroelectric facilities or large-scale industrial cooling processes (Mathieu, 1999). Graywater reuse is not a new technology, not even within municipal contexts in the State of Colorado. One of the first and most notable examples of graywater applications exists in the Front Range city of Colorado Springs. Starting in the early 1960s, Colorado Springs installed a dual distribution system for irrigation (Mathieu, 1999). Watering city parks and green spaces with non-potable gray water, the city produces about 1,250 acre-feet per year at a cost of approximately $11,000 per acre-foot (Mathieu, 1999).

Presently, Denver Water maintains a network of pipelines for treated wastewater that goes to irrigation and cooling towers. These pipelines utilize about 92 acre-feet of graywater per day, or over 33,000 acre-feet per year (Finley, 2014). Indirect reuse is already used by several cities on the Front Range, including the City of Aurora. Indirect reuse involves filtering partially treated wastewater through riverbanks, thus utilizing natural processes to remove the majority of the largest contaminants. The water is then treated in a state-of-the art plant, and the cleaned wastewater, is blended with water drawn from traditional surface rights to augment municipal supplies (Finley, 2014).

The historically high costs of developing a graywater infrastructure has acted historically as the largest barrier to the adoption of graywater reuse as a water resource management strategy. In addition, the contaminants removed from the graywater during the treatment process pose a disposal challenge and increase the operating costs (Finley, 2014). However, the costs of graywater are decreasing, particularly when the water is treated to a lower quality level and reused for non-potable applications. Non-potable graywater can be produced for as little as $7,000 per acre foot (SWSI, 2011), whereas potable reuse is estimated at $13,500 per acre-foot.

In some contexts, the potential for graywater to serve as a major water resource is growing. By 2050, water providers have the potential to develop an estimated 200,000 acre-feet of annual direct and indirect reuse (Western Resource Advocates, 2011). In the Northern Water boundaries, all return flows are claimed and reserved on behalf of Northern Water for subsequent use for downstream diverters in accordance with the Bureau of Reclamation Contract. This means that water obtained through the Colorado Big Thompson system can only be used once and is not available for reuse by the original users (Northern Water Conservation and Management Plan, 2011). Consequently, only non-Colorado Big-Thompson water—about 15,000 acre-feet—is projected to partake in graywater reuse for the Northern Front Range (Western Resource Advocates, 2011).

Criteria: Assessing Water Management Alternative Outcomes

Efficacy

Efficacy refers to the ability of a policy or alternative to realize its objectives under optimal conditions of delivery (Flay, et al., 2005). A complete analysis of efficacy should consider specific goals, and specific measurable, outcomes. Considering the efficacy of water management alternatives in Northern Water, efficacy can be described in terms of the ability of the alternative to close the supply-demand gap of 110,000 acre-feet projected for the year 2050. Efficacy for the alternative is measured as a percentage of the projected 2050 supply-demand that could ideally be met by the selected alternative in terms of potential acre-feet produced. Given the uncertain nature of population growth and in particular, climate change, the efficacy measure used in this study applies only to the current state of knowledge; future studies should measure efficacy based on the most recent data and projections.

Cost-Effectiveness

Cost-effectiveness analysis (CEA) is applicable when not all costs and benefits of a project can be feasibly measured. CEA is a form of economic analysis that compares the costs and outcomes of two or more courses of action (Bardach, 2012). It is generally aimed at choosing the least costly option or combinations of options to achieve a given objective. CEA is achieved through a multi-step procedure. First, the environmental target to be met is determined. Second, alternative measures to achieve the objective are identified. Third, the potential effectiveness of measures is assessed. Fourth, the costs of implementing the measures are estimated. Fifth, alternative options of combinations are assessed based on their costs per unit of outcome (Approach taken from: "Cost effectiveness analysis in the implementation of the Water Framework Directive: A comparative analysis of the United Kingdom and Spain, Ortega & Balana, 2012). CEA is useful in comparing alternative, or cumulative, ways of attaining a given level of benefits. CEA can yield the discounted economic costs of achieving a unit of conservation.

The CEA framework was used to analyze the cost-effectiveness of the water supply management alternatives presented in the alternatives section of this paper. The CEA completed in this thesis identified the target as closing the projected supply-demand gap in Northern Water (110,000 acre feet by 2050) (NCWCD, 2012), and the per-unit cost was based upon the cost per acre-foot of water supply produced by the given alternative.

Robustness and Improvability

Robustness can be generally understood as the ability to withstand or survive external shocks; to be stable in spite of uncertainty. Robust decision methods provide solutions that trade-off among different risks and multiple objectives to allow decision makers to confront a list of unknowns. And robustness analysis is increasingly becoming a well-established criteria because it provides a solid foundation for establishing a practice of adaptive management analysis. It can reveal load-bearing assumptions behind our reasoning, and assist in discovering decision options that promote adaptation and learning (Bankes, 2010). Improvability complements robustness by allowing for the modification of alternatives; improving designs in response to feedback to ensure that the policy outcomes will still prove to be satisfactory despite obstacles (Bardach, 2012). Robust and improvability decision methods:

- Can produce actionable decisions in the face of uncertainty
- Facilitate developing adaptive plans and strategies by discovering warning conditions of failure scenarios that can be used to trigger adaptive mechanisms
- Support mixed initiative planning
- Identify alternatives whose performance is largely insensitive to uncertainties

Feasibility

A feasible policy must not violate constitutional, statutory or common law rights. However, as legal rights can change, policies can be considered that have some legal precedence or are currently being considered by lawmakers (Bardoch, 2012). As in any policy, the legality serves as a relatively limiting or enabling factor. In the case of Northern Water, the alternatives will be subject to both the laws governing the agreements between the district and the Bureau of Reclamation, contracts with existing shareholders and municipalities, and Colorado Water Law. In addition to legal feasibility, the feasibility criterion applied in this thesis relates to political acceptability in terms of support from relevant stakeholders. Feasibility, as applied to this thesis, also reflects the projected support level from Northern Water's Board of Directors given their articulated mission statement and priorities.

Methodology

The literature review conducted in this thesis included a review of the challenges faced by water providers, particularly Northern Water, in the face of population and climate change. The research focused on providing a thematic overview of adaptation, adaptive capacity building, and most notably, adaptive management to deal with these challenges. Literature searches were conducted through library and journal databases at the University of Colorado, Boulder, Google Scholar and the Northern water website. Literature was also found through bibliographic reviews of aforementioned articles and through recommendations made by advising members of the Honors Thesis committee. The source types included peer-reviewed print and non-print journal articles, advisory policy briefings, industry related documents, books, and scientific publications written by experts familiar with the specific institutional and infrastructural mechanisms of adaptive water management and Northern Water. Key elements and findings from each study were pulled and combined in order to determine how to address Northern Water's supply-demand gap and planning challenges. There were numerous water management approaches to consider for Northern Water, but the combined background and adaptive management literature strongly supported an alternative comparison and analysis process (Pahl-Wostl, 2007) (Hermans & Erickson, 2007) (Medina, et al., 2008) . Accordingly, this thesis utilizes an alternative selection and analysis framework that is conducive to the adaptive management lens.

The structure of the alternative selection process in this thesis was patterned after the analysis framework articulated by Eugene Bardach in “A Practical Guide for Policy Analysis: The Eightfold Path to More Effective Problem Solving” (2012). First, extensive background information was collected for the Northern Water System in order to define problems and identify potential intervention strategies in the complex system with many acting impact factors and constraints (Bardach, 2012). Next, a list of alternatives was generated with regard to this background information and the predominant management and planning strategies used currently by Northern Water and other water providers. Lastly, the list of alternatives was pared down to four alternative water management strategies by excluding alternatives that were non-realistic, did not effectively alleviate the 110,000 acre-feet supply-demand gap faced by Northern Water in any substantive way, and were simply iterations of another stated alternative. The selection process yielded the following four alternatives:

- Alternative water transfers
- Firming projects
- Conservation measures
- Graywater reuse

The alternatives included in this thesis were of significantly different nature providing similar benefits with different impacts or are design-related alternatives that alter the details or scope of the proposed action (Hill & Ortolano, 1978). The inclusion of these final alternatives aligned with the recommendations for considering various management actions under the world's predominant environmental policies, including the National Environmental Policy Act (Bear, 2003).

Following the selection of four alternative adaptive management actions for Northern Water, criteria for the evaluation of these alternatives were developed with strong consideration of the supply-demand gap, the stated mission and priorities of Northern Water's Strategic Plan, as well as the adaptive management framework presented in the literature review. Ideally, criteria and sub-criteria hierarchies would have also take into consideration stakeholder judgment through the administration of a survey (Linkov, et al., 2006), but the time restraints of the thesis limited the criteria selection to the literature review. Given the lack of a stakeholder survey gathering data as to the relative importance of each criterion in regards to the other criteria, all criteria for Northern Water were weighted equally. These criteria were:

- Efficacy (in terms of percent of projected supply-demand gap closed)
- Cost-effectiveness (cost of the alternative to produce one acre-foot of water)
- Robustness & Improvability (ability of the supply to absorb, adjust to changes)
- Feasibility (ability to overcome legal/institutional barriers to adaptation)

With the criteria established, it was subsequently necessary to create an alternative outcomes matrix to bring alternatives and criteria together in order to complete the comparative process (Bardach, 2012). The outcomes matrix format—established by Bardach--was a tabulated array of adaptive water management alternatives and criteria. Alternatives formed the vertical down rows, and the evaluative criteria displayed across the horizontal columns of a singular table. Each cell contained the projected outcomes of the row alternative as assessed by reference to the column criterion (Bardach, 2012). The outcomes of the four adaptive water management alternatives and the four selected criteria for Northern Water were described qualitatively (i.e., High, Medium, Low), but also quantitatively (percent, $/acre-foot). For example, the three possible criteria outcomes for the nexus of one alternative and the "Improvability and Robustness" criteria might be "Low," "Medium," and "High," whereas at the interplay of the same alternative with another criteria the possible outcomes might be 30%, 60%, and 80%.

In order to compare systematically these disparate quantitative and qualitative outcomes within the matrix, this thesis utilized a multi-criteria decision analysis (MCDA) process implemented by Linkov, et al., 2006. There are multiple approaches to the MCDA process, including a relative ranking scale of alternatives, but this thesis utilized the multi-attribute utility theory (MAUT) device. MAUT is an optimization algorithm that uses numerical scale scores to quantify the merit of each individual alternative relative to the performance of that alternative under ideal conditions regardless of differences in metrics between data sets, as these (Linkov, 2006). To compare the alternative water management outcomes for Northern Water, criteria scale score conversions were developed from the performance of alternatives with respect to individual criteria (Linkov, 2006).These scale scores were applied to the outcomes of the alternatives matrix and then the individual scale scores were aggregated and averaged across cell columns and rows (Linkov, 2006). The resulting scale data, combined with the qualitative and quantitative results from the outcomes matrix formed the basis of the results, which the thesis used to rate alternatives and make recommendations for Northern Water as part of adaptive management strategy.

Table 1-Outcomes Matrix: Northern Water Supply Adaptive Water Management Alternatives (MAUT Score)

	Efficacy (% of Projected 2050 Annual Supply-Demand Addressed)	**Cost Effectiveness ($/acre-foot of water produced)**	**Robustness & Improvability (Low, Medium-Low, Medium, Medium-High, High)**	**Feasibility (Low, Medium-Low, Medium, Medium-High, High)**	**Aggregate MAUT Score for Given Alternative**	**Average MAUT Score for Given Alternative**
Alternative Water Transfers	73,000/110,000 66% **(0.66)**	14,000-34,000 **(0.70-0.10)**	Medium Robustness, Medium Improvability **(0.50) avg.**	Medium **(0.5)**	**1.76- 2.36**	**0.44-0.59**
Water Firming Projects	40,000/110,000 36% **(0.36)**	16,200-32,200 **(0.59-0.19)**	High Robustness, Low Improvability **(0.50) avg.**	Medium-High **(0.8)**	**1.85-2.25**	**0.46-0.56**
Conservation Measures	32,491/110,000 30% **(0.30)**	5,200-11,098 **(0.96-0.79)**	Medium-Low Robustness, High Improvability **(0.55) avg.**	High **(0.9)**	**2.54-2.71**	**0.64-0.68**
Graywater Reuse	15,000/110,000 14% **(0.14)**	7,000-13,500 **(0.93-0.62)**	Medium-Low Robustness, Medium-Low Improvability **(0.30) avg.**	Medium **(0.5)**	**1.56-1.87**	**0.39-0.47**
Aggregate MAUT Score for Given Criteria	**1.46**	**1.70-3.18**	**1.85**	**2.70**		
Average MAUT Score for Given Criteria	**0.37**	**0.43-0.80**	**0.46**	**0.68**		

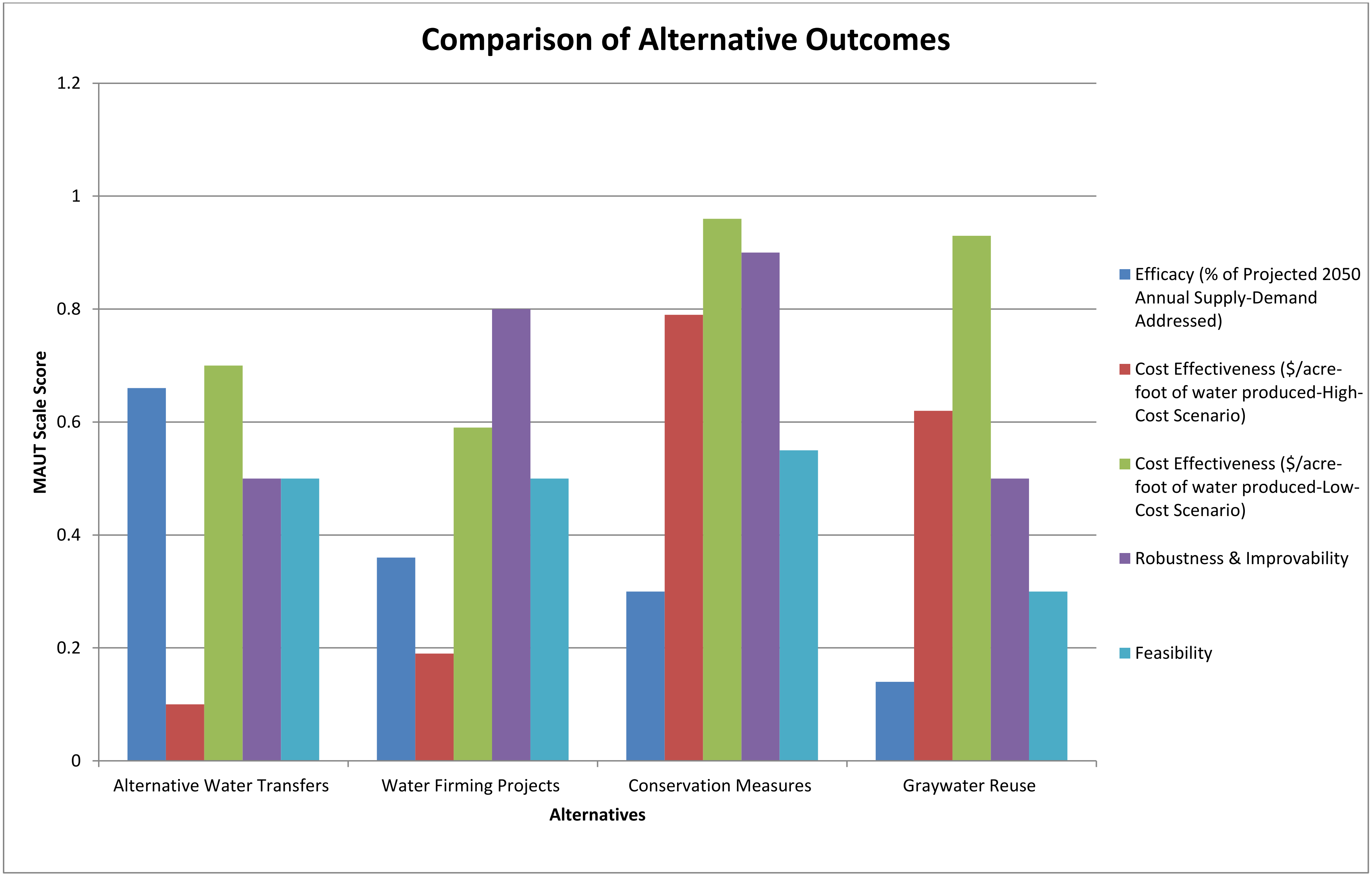
MAUT Scores derived from Criteria Scale Score Conversions.* See Table Below.

Table 2-*Criteria Scale Score Conversions

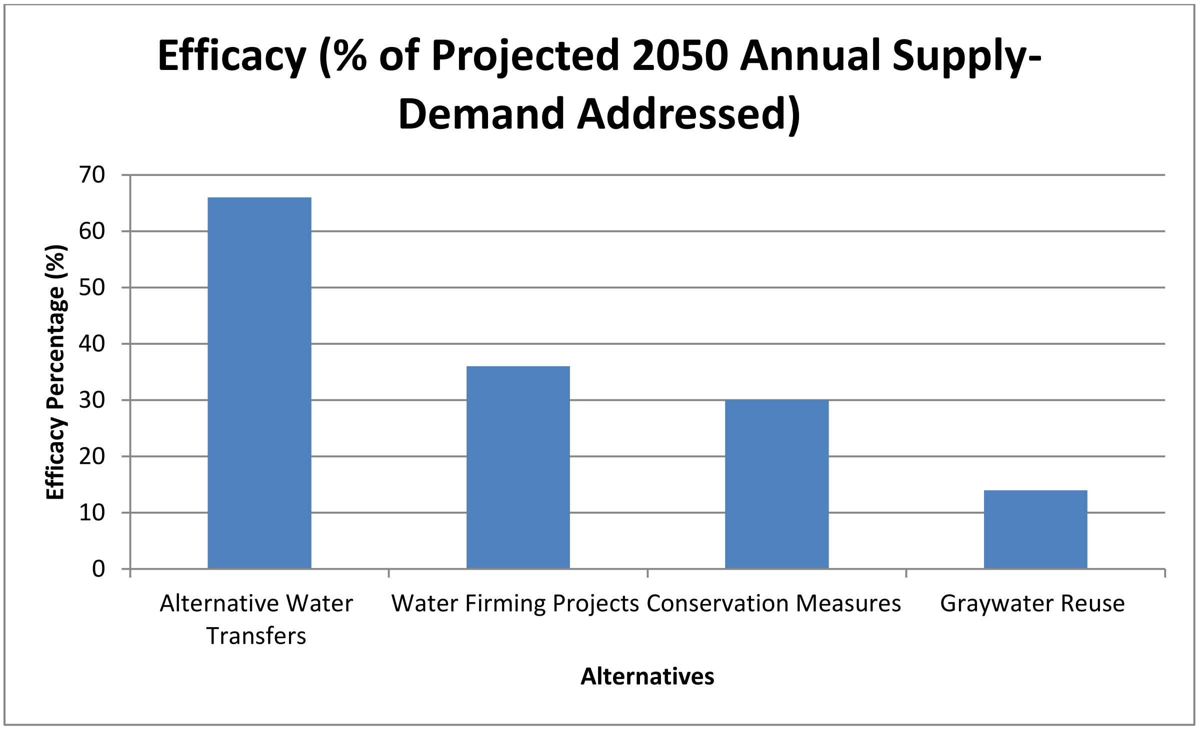
Efficacy (% of Projected 2050 Supply-Demand Addressed)	Efficacy MAUT Scale Score (0.1-1.0)	Cost Effectiveness ($/acre-foot of water produced)	Cost Effectiveness MAUT Scale Score (0.1-1.0)	Robustness & Improvability (Low, Medium-Low, Medium, Medium-High, High)	Robustness & Improvability MAUT Scale Score (0.1-1.0)	Feasibility (Low, Medium-Low, Medium, Medium-High, High)	Feasibility MAUT Scale Score (0.1-1.0)
10%	0.10	34,000	0.10	Low	0.10	Low	0.10
20%	0.20	31,000	0.20	Low	0.20	Low	0.20
30%	0.30	28,000	0.30	Medium-Low	0.30	Medium-Low	0.30
40%	0.40	25,000	0.40	Medium-Low	0.40	Medium-Low	0.40
50%	0.50	22,000	0.50	Medium	0.50	Medium	0.50
60%	0.60	17,000	0.60	Medium	0.60	Medium	0.60
70%	0.70	14,000	0.70	Medium-High	0.70	Medium-High	0.70
80%	0.80	11,000	0.80	Medium-High	0.80	Medium-High	0.80
90%	0.90	8,000	0.90	High	0.90	High	0.90
100%	1.00	5,000	1.00	High	1.00	High	1.00

Results

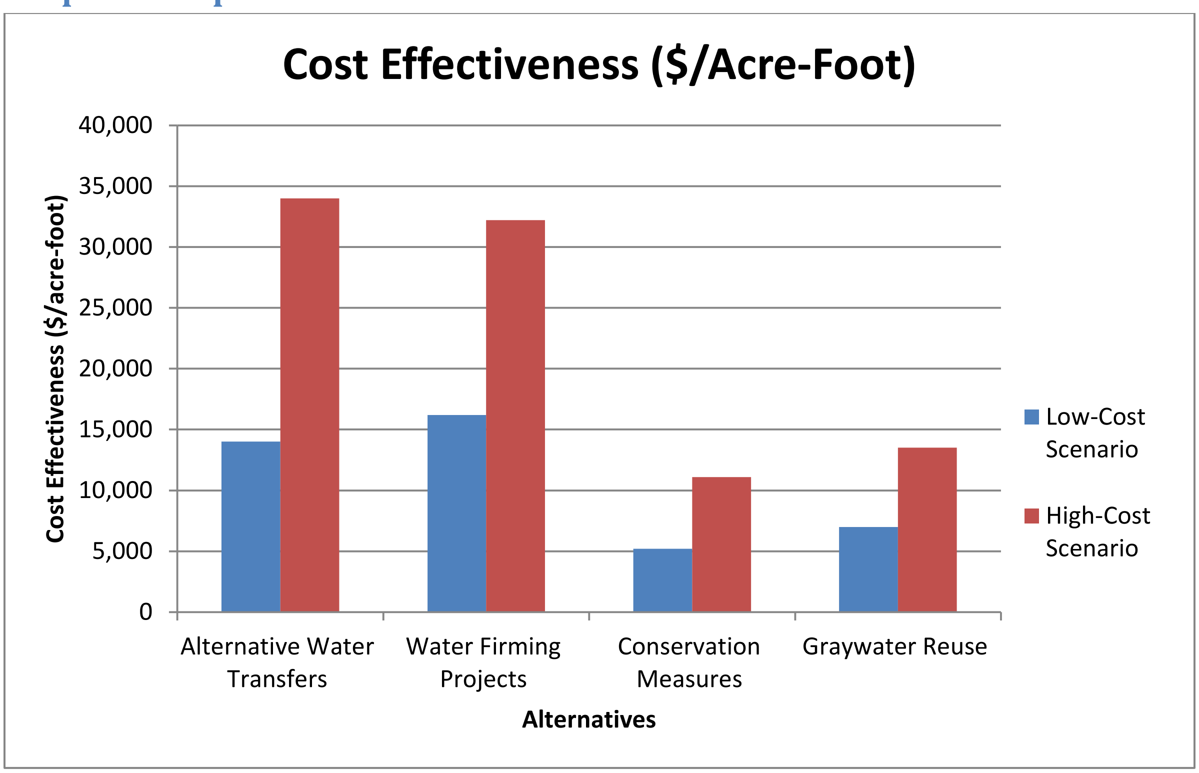
Graph A-Comparison of Alternative Outcomes



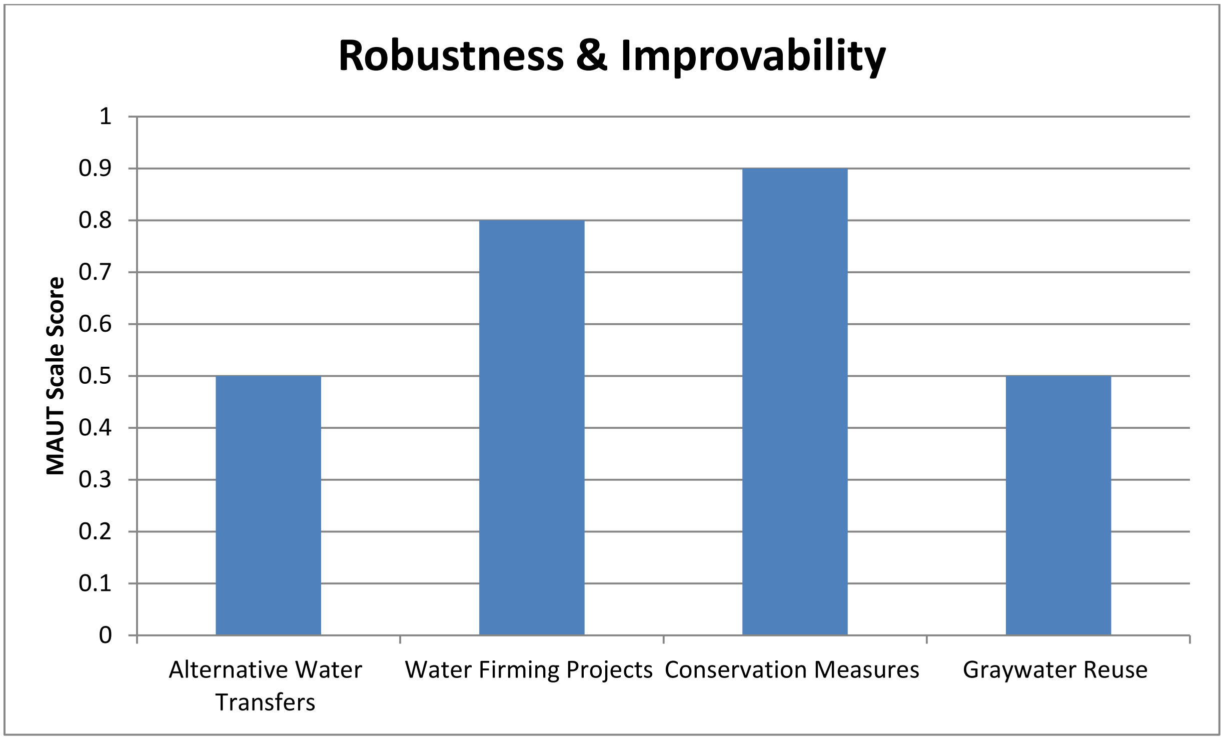
Graph B-Comparative Alternative Efficacy



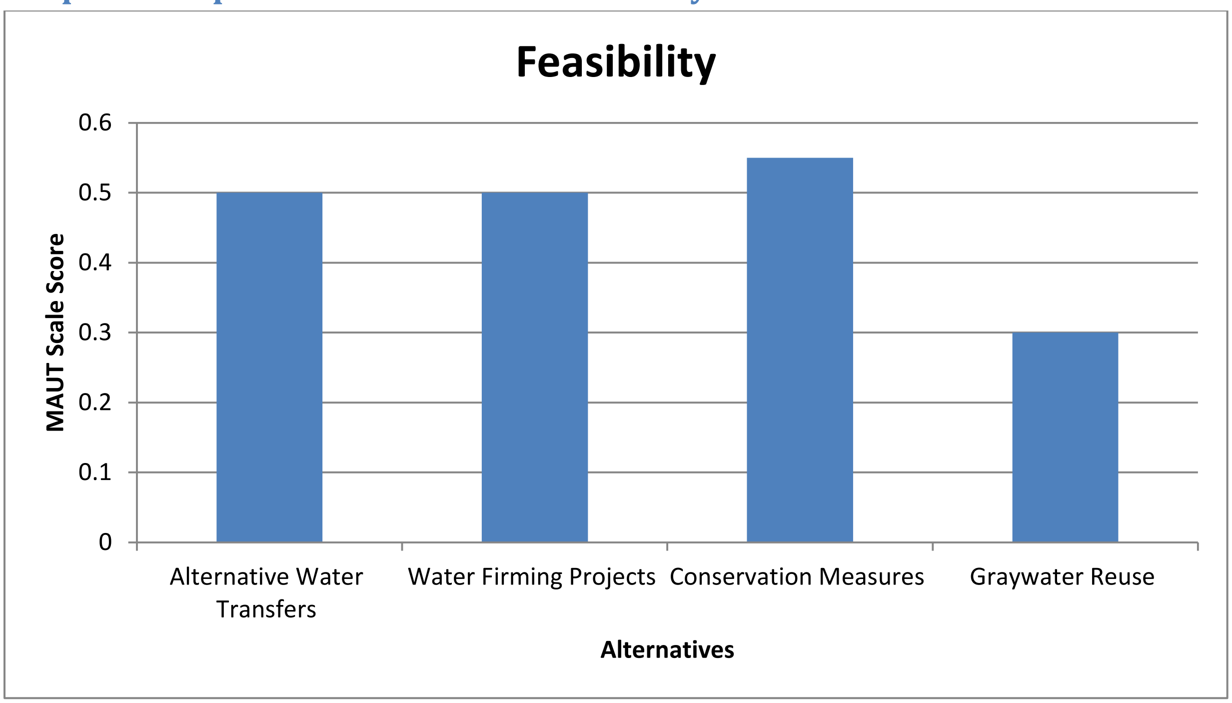
Graph C-Comparative Alternative Cost-Effectiveness



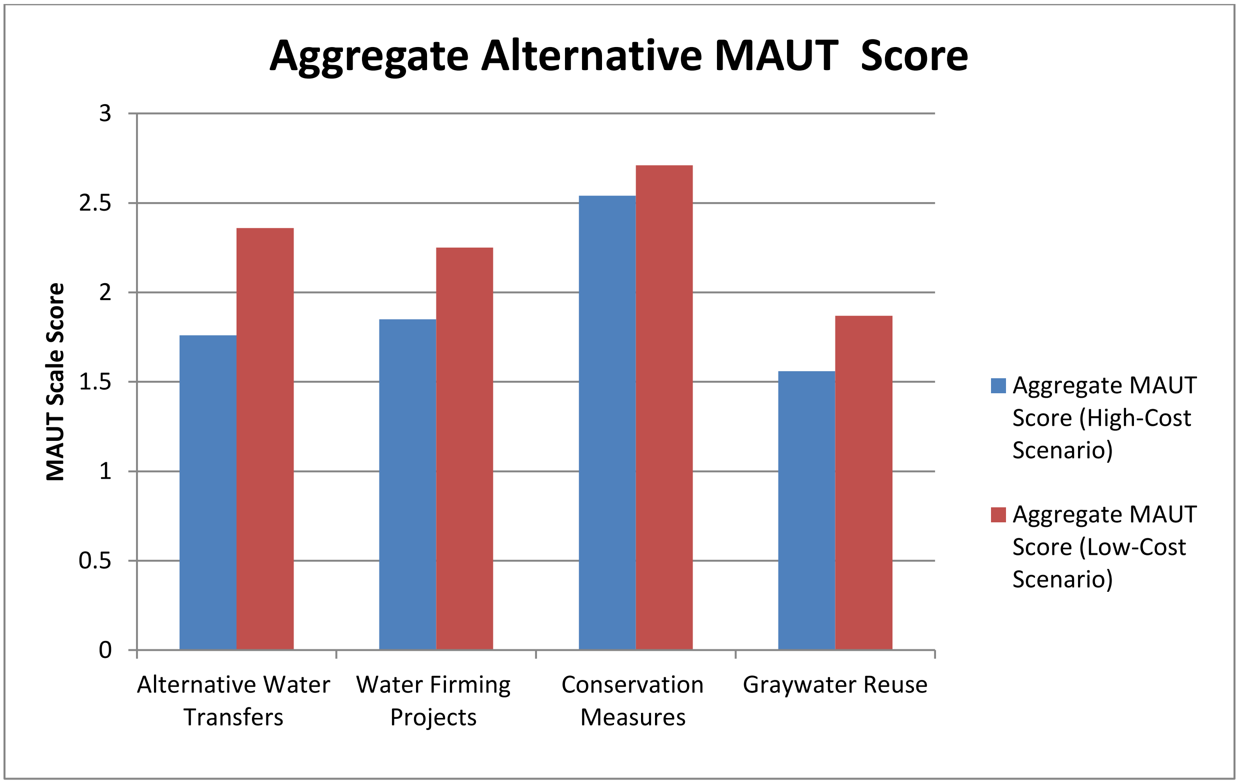
Graph D-Comparative Alternative Improvability & Robustness



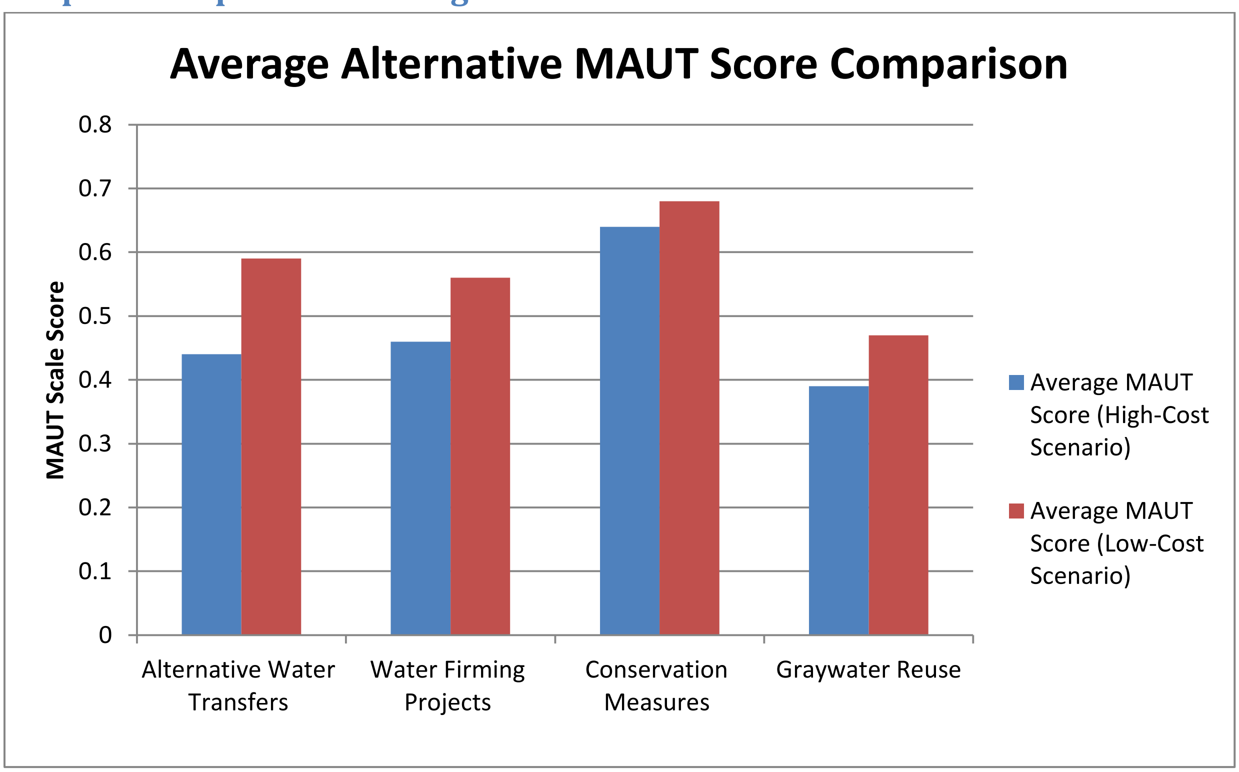
Graph E-Comparative Alternative Feasibility



Graph F-Comparative Aggregate Alternative MAUT Scores



Graph G-Comparative Average Alternative MAUT Scores



The findings of the alternatives outcome matrix were organized according to the four selected alternatives for Northern Water: Alternative water transfers, firming projects, robustness and improvability, and feasibility.

Alternative water transfers

The application of the evaluative criteria to alternative water transfers produced quantitative and qualitative data and descriptors in the outcomes matrix. These results revealed that alternative water transfers could provide an additional 73,000 acre-feet to municipal users in Northern Water by 2050 (Graph B). **Alternative water transfers had the highest efficacy among the selected water management alternatives,** with the potential to close 66 percent of the projected 110,000 acre-foot shortfall (Graph B). Given that the literature regarding cost effectiveness of all alternatives held highly variable projections on cost, the cost-effectiveness results were provided for all alternatives as both a low-cost and a high-cost scenario. Under a low-cost scenario, alternative water transfers provided the third best cost-effectiveness at $14,000 per acre-foot of water produced (Graph C). **Under the high-cost scenario, water transfers were the least cost-effective alternative** at $34,000 per acre-foot (Graph C). In determining robustness and improvability of alternative water transfers, each alternative received a MAUT scale score out of a potential 1.0, with a score of 1.0 signifying perfect performance of the given alternative. Given that alternative water transfers provided both medium robustness and medium improvability, alternative water transfers received a MAUT scale score of 0.5 (Graph D). Alternative water transfers also received a medium outcome rating for feasibility, which translated to a MAUT score of 0.5 (Table-1) (Graph E).

Firming projects

Firming projects was projected to produce 40,000 annually available acre-feet of new water resources for Northern Water by 2050 (Graph B). Second only to alternative water transfers, the matrix rated efficacy outcomes for water firming projects at 36 percent, which received a MAUT scale score of 0.36 (Table 1) (Graph B). While efficacious, firming projects perform more poorly than several other alternatives with regards to their cost-effectiveness. Under the low-cost scenario, firming projects can produce new water resources for $16,200 per acre-foot (Table 1). **Under the low-cost scenario, firming projects present the least cost-effectiveness option**; thusly, the alternative received the lowest MAUT scale score—0.59—of all alternatives under the low-cost scenario. Under the high-cost scenario, water firming projects were estimated to cost approximately $32,200 per acre-foot (Table-1). While slightly cheaper than alternative water transfers ($34,000 per acre-foot), firming projects cost significantly more than conservation methods and graywater reuse. Under the high-cost scenario, firming projects earned a MAUT scale score of 0.19 (Table 1). To provide an example of the cost of firming projects, the Windy Gap Firming Project alone is projected at $285 million dollars (NCWCD, 2014 “Windy Gap Firming Project”). This firming alternative and the NISP projected combined would supply only about 40,000 acre-feet to Northern Water (Graph C).

While firming projects have low improvability due to their extensive infrastructure, they have extremely high robustness (Table 1). The results of the matrix reflect these characteristics, as firming projects earned a robustness and improvability score of 0.8 (Graph D). The results also yielded a feasibility score of 0.5, which reflects the “medium” rating awarded in the outcomes matrix. This score is equal to the feasibility performance of alternative water transfers (Graph E).

Conservation measures

The alternatives outcome matrix revealed that new water resources cost slightly more than $5,000 per acre-foot under a low-cost scenario (Graph C). Under a high-cost scenario, conservation measures cost slightly more than $14,000 per acre-foot (Graph C). **Under both low-cost and high-cost scenarios, conservation measures presented the most cost-effective water management alternative to increase supplies.** The outcomes matrix results also demonstrated that conservation measures were 30 percent effective, potentially providing an additional 32,491acre-feet of water towards the 110,000 supply-demand gap. Resultantly, conservation measures received a MAUT score of 0.3, which was the second-lowest score awarded for efficacy. In the alternatives outcome matrix, conservation measures received medium-low ratings for robustness and high ratings for improvability.

Robustness outcomes were reflective of the current practice of using conservation measures as a robust adaptation strategy by water providers to absorb the impact of drought, but also factored in the possibility for demand hardening from more extensive incorporation as an alternative (Western Resource Advocates, 2011). Given the robustness and improvability outcomes, **conservation measures claimed the highest MAUT score for robustness and improvability with a score of 0.55** (Graph D). Concerning feasibility, **conservation measures received a high rating in the outcomes matrix and a corresponding MAUT scale score of 0.9** (Table 1) (Graph E). With feasibility included, conservation measures outperformed other alternatives in all categories, save efficacy.

Graywater reuse

The literature review showed that Colorado had the potential to develop upwards of 200,000 acre-feet of graywater reuse by 2050 (Western Resource Advocates, 2011). However, Northern Water's graywater reuse was limited to rights not obtained through the Colorado Big-Thompson Project (Northern Water Conservation and Management Plan, 2011). Consequently, the outcomes matrix reported a 15,000 acre-feet potential for Northern Water, which resulted in 14 percent efficacy and a corresponding MAUT scale score of 0.14 (Table 1) (Graph B). Graywater reuse is the least efficacious of the four selected alternatives for Northern Water in terms of closing the projected supply-demand gap. Graywater is, however, the most second most cost effective alternative. The outcomes matrix yielded a low-cost estimate of $7,000 per acre-foot of water produced, and a high-cost estimate of $13,500 per acre-foot (Table 1) (Graph C). These cost effectiveness outcomes resulted in MAUT scores of 0.93 and 0.62, respectively. For the criteria of robustness and improvability and feasibility, graywater reuse scored below other alternatives. **Graywater reuse had a medium-low robustness and medium-low improvability (Table 1), returning a MAUT score of 0.3, the lowest score of all alternatives.** For feasibility, graywater reuse had a medium level outcome, resulting in a MAUT score of 0.5.

General Results

The resulting MAUT scores from the alternative outcomes matrix were aggregated (summed) and averaged to produce cross-criteria and cross-alternative data. For both aggregate and average data, alternative MAUT scores (Graph F) compared the outcomes of each individual alternative (with high and low-cost scenarios for cost effectiveness separated) against every other alternative. **Conservation measures emerged as the strongest water management alternative for Northern Water with an aggregate MAUT scale score of 2.54-2.71 out of a maximum of 4.0 and an average scale score of 0.64-0.68 (Table 1) (Graph F) (Graph G).** Second to conservation in terms of aggregate and average score was Alternative Water Transfers, with an aggregate score of 1.76-2.36 and an average score of 0.44-0.59. Third was firming projects, with an aggregate MAUT score of 1.85-2.25 and an average score of 0.46-0.56. Finally, graywater reuse had the lowest alternative outcomes, with an aggregate score of 1.56-1.87 and an average score of 0.39-0.47.

In addition to comparing the outcomes of alternatives with respect to one another, this thesis investigated the outcomes of one criterion—efficacy. In the methodology, efficacy was calculated as the percent of the supply-demand gap addressed by the alternative (Table 2). The corresponding MAUT scale score was a decimal representation of this percentage. Accordingly, the MAUT scale score also represented the percent of the supply-demand gap addressed. Therefore, the aggregate MAUT score for efficacy across criteria represented the percentage of the 100,000 projected supply-demand gap for Northern Water that could potentially be met by a combination of all alternatives. The aggregate MAUT score of **1.46** (Table 1) demonstrated that even with all alternatives operating under ideal conditions, the strategies would combined, produce 146% of the supply needed to close the gap, which would translate into approximately 160,600 acre-feet of water, with an additional 50,000 acre-feet of water.

Discussion

This thesis investigated what management alternatives should be implemented to close the projected water supply-demand gap while improving the reliability and sustainability of Northern Water system. Drawing from the predominant regional practices, four alternative water management strategies were selected: alternative water transfers; water firming projects; conservation measures; and graywater reuse. The potential outcomes of these four criteria were weighed against evaluative criteria consisting of efficacy (% of 110,000 acre-feet supply-demand gap addressed); cost-effectiveness ($/per acre-foot of water produced); robustness and improvability; and feasibility. Utilizing a multi-criteria decision analysis (MCDA) approach with an applied multi-attribute utility theory (MAUT) scale score conversion of quantitative and qualitative data, outcomes of water management alternatives were made commensurable through a comprehensive comparison matrix.

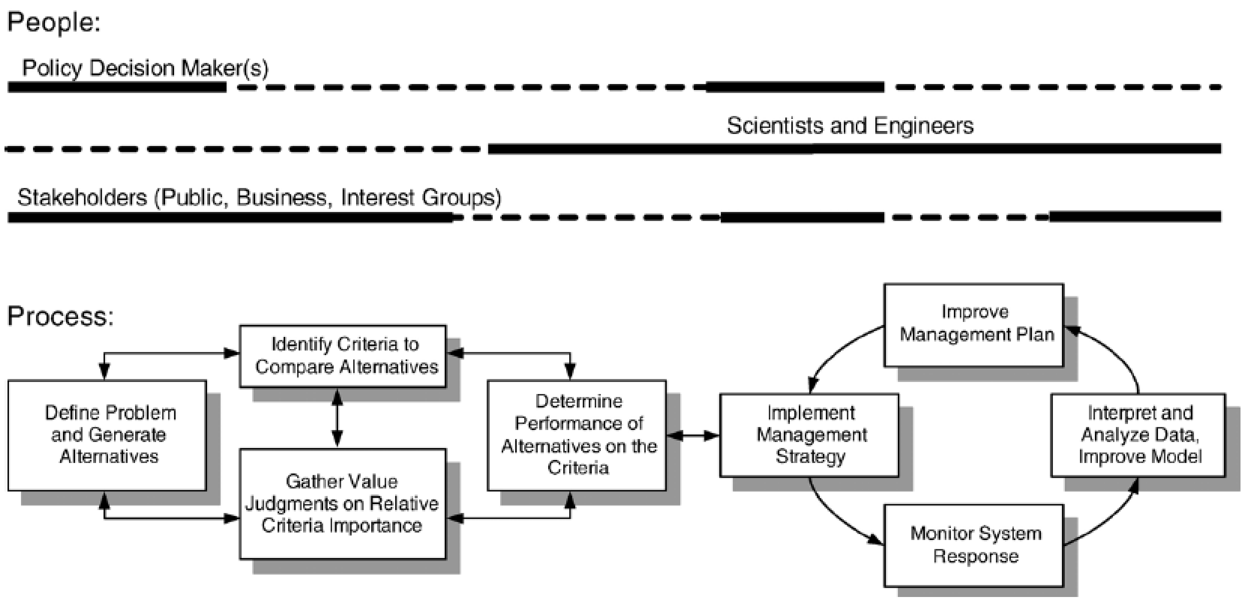
What significance do the results of this thesis bear on water management recommendations for Northern Water? The results of the alternatives outcome matrix demonstrated that when municipal suppliers and agricultural water rights holders are willing and able to temporarily utilize water normally used to irrigate crops, there is potential for all water users to benefit from alternative water transfers (Colby, et al., 2015). Although water transfer agreements presented problems in terms of cost-effectiveness, they outcompeted other options for improving supply (Colby, et al., 2015). In the case of Northern Water, alternative water transfers had the potential to provide over 70,000 acre-feet of new water towards the 110,000 supply-demand gap by 2050 while minimizing the environmental and economic hardships posed by traditional buy-and-dry water transfers.

However, in all other criteria, conservation measures scored highest. Conservation measures achieved the best cost-effectiveness, highest robustness and improvability, and greatest likelihood for legal and institutional feasibility, aligning with Northern Water's stated priorities that center on delivering water, conserving and protecting water supplies, and planning for future water supplies. Water firming projects—specifically the Windy Gap Firming Project and NISP—scored second in efficacy with 40,000 potential acre-feet of additional water supply produced; yet, these firming projects are the least cost-effective alternative under the low-cost scenario. Moreover, graywater reuse also performed poorly in feasibility, robustness, and improvability.

The fact that conservation measures rated so highly in the outcomes matrix suggests that conservation should be used as the primary strategy for a developing a baseline water supply. At $5,000-$14,000 per acre-foot and with a potential to produce 32,491acre-feet of water, conservation measures could address approximately 30 percent of the gap for as little $163 million—half the cost of a water firming project of comparable size. Furthermore, conservation measures could alter use instantly through a number of mechanisms including water restrictions and water pricing. However, conservation measures cannot serve as the only water management strategy for Northern Water. Providing an adequate water supply will involve implementing a mix water projects, conservation, reuse, and agricultural transfers all of which should be pursued concurrently (SWSI, 2011). The resulting aggregate criteria MAUT score supported this finding, as the score demonstrated that order to close the gap, multiple alternatives would be necessary.

Limitations

The results of this thesis suggest that multiple alternatives must be implemented to address the supply-demand gap. Furthermore, the utilization of a portfolio, rather than a single alternative, can be naturally linked with an adaptive management framework. As a consequence of uncertainty, adaptive management holds that a set of alternatives should be explored and tracked to gain information about the outcomes of different courses of action (Linkov, et al., 2006). The adaptive framework proposed by Linkov, et al., 2006, represents the iterative process used to make natural resource management decisions. After an alternative is chosen or analysis, criteria are identified, the performance of the alternative is assessed in regard to the criteria, and the results are used to inform and re-rank alternatives as well as criteria. While this thesis produced alternative outcome comparisons and recommendations based on this model, it is important to remember its limitations in terms of scope and content.



Adaptive Management Framework: Figure from Linkov, et. al, (2006).

First, under ideal conditions, the criteria utilized by the MAUT process are not only developed by key stakeholders regarding the management of the particular resource, but also are weighted to reflect and respond to the perceived importance of these criteria, as seen in the framework below (Linkov, et al., 2006). In the design of this thesis, stakeholders were not included in the development and weighting of alternative outcome criteria due to limited time and resources constraints. Instead, criteria were derived from the literature and from the stated mission and strategic priorities of Northern Water. Furthermore, the evaluative criteria were left unweighted, rather than to reflect a potential bias. A recommendation for future research regarding the application of adaptive water management in Northern Water would ideally approach stakeholders to determine the expressed goals of the alternatives and criteria weightings. Finally, this thesis did not implement a management strategy, and thusly could not use a system response to inform the performance and selection of alternatives.

Second, the scope of this thesis was limited exclusively to application within Northern Water. Although it is not immune to the management challenges such as population growth and the increasing impacts of climate change at a global scale, Northern Water possesses a unique institutional environment, even within the state of Colorado. For example, a study for Denver Water-a neighboring water resource entity and provider—would have resulted in drastically different alternatives outcomes and recommendations. While most water providers with transbasin diversion water rights on the Colorado Front Range have the ability to reuse this water, Northern Water largely does not hold this same capacity. The Colorado Big-Thompson Project—where the majority of Northern Water's resources are derived –was developed as a supplemental water source for all downstream users and cannot be reused by shareholders in the Conservancy District. Subsequently, the provisions associated with Northern Water's initial mandate severely limit the potential to develop graywater reuse as compared to other water management entities in close geographic proximity and facing similar management challenges.

Application: A Novel Approach to Resource Management

Population growth and climate change present water providers with management challenges to maintaining the supply, affordability, and reliability of water resources. In the Northern Colorado Water Conservancy District (Northern Water), population growth poses a 110,000 acre-feet supply-demand gap by the year 2050. Moreover, climatic shifts will simultaneously increase uncertainty of the timing, type, and distribution of expected precipitation. In many regions, the availability of water in the next century will depend on the capacity to manage increasingly precarious water systems in a naturally water-limited setting. The needs of growing population centers have largely been filled by agricultural urban water transfers which has already, and will likely continue to result in loss of agricultural lands, harm to ecosystems and economies, and decreases in water supply reliability. These negative impacts have highlighted the need for paradigmatic shifts in resource management. Unlike the dominant predict-and-control approaches that have governed resource management for the past centuries without critical analysis regarding their appropriateness or long-term performance, the 21st century will demand water management that that can absorb and respond to uncertainties (Pahl-Wostl, 2007).

Water resource decisions are being made today, with implications extending far into the future. On December 19, 2014—during the course of this study—the U.S. Bureau of Reclamation issued a Record of Decision for the Windy Gap Firming Project, permitting Northern Water to begin construction on its Windy Gap Firming Project (NCWCD, 2014 "Windy Gap Firming Project"). As Northern Water moves forward with this project, it has committed itself to the expansion of firming projects and new storage, perhaps without considering the outcomes of the alternative strategies for improving supplies that are more cost-effective, robust, improvable and feasible. By encouraging the expansion of storage without additional constraints, the Windy Gap Firming project might be establishing the very conditions that will render it inadequate; providing enough water to encourage additional use that will eventually exceed the project's ability to satisfy the demands placed upon it. Management decisions in Northern Water and across the world demonstrate the need for a novel approach to water resource management. This thesis presents such an approach through the development of available management options, the selection of evaluative criteria, and the comparative analysis of outcomes through the MCDA and MAUT processes. The integration of an extensive regional study and literature review create a strong collective vision for decision-makers and potentially even stakeholders, placing the managing water entity in a position to pursue systematic transformations that are necessary to address the long-term and uncertain impacts of population growth and climate change.

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